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A Method for Evaluating Diagnostic Aid Systems in Army Land Vehicle Maintenance

Gary F. Mills, Kathleen A. Wolf

A Report prepared for

DEFENSE ADVANCED RESEARCH PROJECTS AGENCY

Rand
SANTA MONICA, CA. 90406

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PREFACE

Operating and support (O&S) costs are consuming an increasingly large portion of the defense budget. As O&S costs have grown, so has interest in ways of reducing them while enhancing the readiness and availability of U.S. military equipment. One potential way of attacking both problems is to use diagnostic aid systems to lower the cost of maintaining military equipment and reduce its downtime. Many such diagnostic aid systems have been developed or proposed by military agencies and civilian contractors.

This report, part of a study for the Defense Advanced Research Projects Agency (ARPA), examines ways of evaluating the potential utility of diagnostic aid systems,* particularly their use in maintaining the automotive subsystems of U.S. Army land vehicles. In addition, it discusses difficulties in obtaining accurate data on current maintenance practices and costs, using the 1/4 ton truck (M151A1) as an example. The results should be useful to agencies concerned with the development and procurement of diagnostic aid systems, and with Army land vehicle maintenance costs.

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*Specific diagnostic aid systems and hardware are considered in other parts of the ARPA study. Also included are a survey covering many aspects of Army vehicle maintenance, and the design and test of a monitoring system to record vehicle use and maintenance.

SUMMARY

This report examines currently available Army land vehicle maintenance data and describes the development of a general method for evaluating diagnostic aid system concepts. Analytic models designed during this study describe the interactions between diagnostic aid systems and vehicle maintenance.

The methodology is based on two fundamental assumptions: first, that current vehicle operating and maintenance practices embody a number of problems that cause maintenance costs to be higher than necessary, and, second, that diagnostic aid systems perform functions that can reduce or eliminate these problems. The problems are of two types: those that increase the frequency of maintenance by decreasing vehicle reliability, and those that increase the cost per maintenance action (parts and/or labor) by decreasing vehicle maintainability. The difference between maintenance costs in the absence of diagnosis and costs with all such problems eliminated is a measure of the maximum potential leverage for diagnostic aid systems.

Two models were designed to implement this methodology. The Cost Savings Model (CSM) employs a cost factor approach, whereas the Maintenance and Diagnostics Analysis Model (MADAM) uses a reliability/maintainability approach. MADAM is an evolutionary development and refinement of the CSM, and uses much of the same terminology; MADAM was designed after existing models were examined and found unsuitable for our study. Given as inputs the number of miles (or hours) of operation, the reliability/maintainability

characteristics of up to six vehicle subsystems, problem magnitudes, and diagnostic effectiveness, MADAM estimates vehicle maintenance costs with and without the use of a diagnostic aid system. MADAM is calibrated to 1/4 ton truck (M151A1) maintenance costs using field data, test data, and subjective estimates where data are unavailable. Several analyses illustrate the abilities of both models to identify the most important maintenance problems, examine the effects of changes in problem magnitudes or diagnostic effects, and estimate the potential savings resulting from the use of a particular diagnostic aid system.

The most serious limitation of this methodology is the lack of good maintenance data, a fact which mandates a parametric approach. Some data are nonexistent and must be estimated; others are available but inconsistent from one source to another.

Since the early 1960s, the Army has employed several data collection and processing systems. An exhaustive attempt to collect data on every maintenance action was instituted under TAERS (the Army Equipment Records System), in use from 1962 to 1969. Much of the TAERS data base proved to be inaccurate, since there was little or no verification of input. The successor to TAERS, the Army Maintenance Management System (TAMMS), although reduced in scope, suffers from many of the same limitations. A new system, the Standard Army Maintenance System (SAMS) is now under development; SAMS is intended to standardize and simplify all aspects of maintenance management and reporting. Under Sample Data Collection (SDC) plans, implemented in 1972, data are collected over a limited time period on a selected

sample of a given vehicle type. A fully controlled form of SDC, "intense" SDC, is probably the most effective system to date, but it can be very expensive. Other sources of data are vehicle tests (which may not be representative of experience in operating units) and special collection efforts at post/unit level (usually aimed at developing local cost factors of limited applicability). Because of radical differences in philosophy and management objectives, commercial experience (e.g., from trucking firms) is not a good analog for Army experience.

Data problems are not unique to the Army, but fragmentation of the Army's data sources, and bureaucratic, organizational, and cost considerations do affect data collection efforts. As an illustration of data problems, maintenance data for the 1/4 ton truck (M151A1) were extracted from several sources and found to differ significantly both within and across sources. Because of the condition of the currently available data, any approach to evaluating diagnostic aid systems must of necessity be parametric. In spite of the time and effort the Army has devoted to data collection and processing, no one knows with any certainty what it currently costs (or should cost) to maintain the various types of Army land vehicles, although estimates of total fleet maintenance expenditures are available.

ACKNOWLEDGMENTS

We would like to express our appreciation to the many people who provided valuable information and assistance during the course of this study, in particular our colleagues Richard Salter and William Whelan. Our special thanks are extended to Rand reviewers Chauncey Bell, Charles Kelley, and Richard Wise, and to those persons outside Rand who reviewed earlier drafts of this report and made many valuable comments and suggestions.

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GLOSSARY

AMC	Army Materiel Command (now DARCOM)
AMDF	Army Master Data File
AMSAA	Army Materiel Systems Analysis Activity
AR	Army Regulation
ARENBD	Armor and Engineer Board
CONUS	Continental United States
CSM	Cost Savings Model
DARCOM	Development and Readiness Command (formerly AMC)
DA	Department of the Army
DS	Direct Support (maintenance level)
FORSCOM	Forces Command
FSN/NSN	Federal Stock Number/National Stock Number
GS	General Support (maintenance level)
LSA	Logistics Support Analysis
MAC	Maintenance Allocation Chart
MACRIT	Manpower Authorization Criteria
MADAM	Maintenance and Diagnostics Analysis Model
MAWLOGS	Models of the U.S. Army Worldwide Logistics Systems
MMC	Maintenance Management Center (formerly Logistics Data Center, now Materiel Readiness Support Activity)
ORG	Organizational (maintenance level)
O&SCMIS	Operating and Support Cost Management Information System
RCA	Radio Corporation of America
SAMS	Standard Army Maintenance System

SDC	Sample Data Collection
STE/ICE	Simplified Test Equipment/Internal Combustion Engine powered materiel
TACOM	Tank-Automotive Command (now TARADCOM/TARCOM)
TAERS	The Army Equipment Records System
TAMMS	The Army Maintenance Management System
TARADCOM	Tank-Automotive Research and Development Command (formerly TACOM)
TARCOM	Tank-Automotive Readiness Command (formerly TACOM)
TO&E	Table of Organization and Equipment
TRADOC	Training and Doctrine Command
VETMIS	Vehicle Technical Management Information System

I. INTRODUCTION

For several years, the Department of Defense has evidenced a growing interest in accurately estimating and significantly reducing the operating and support costs of military equipment. One way to reduce maintenance costs by the application of technology is to use advanced diagnostic aid systems. With this possibility in mind, ARPA asked Rand to examine the potential utility and cost benefits of advanced diagnostic aid systems for Army land vehicle maintenance; the request was later expanded to include an in-depth examination of Army land vehicle maintenance data.

One part of the resulting Rand study has been devoted to developing a scheme to evaluate diagnostic aid system concepts in terms of potential reductions in maintenance costs. A methodology was developed under the assumption that current maintenance equipment, resources and operating practices embody a set of problems that cause maintenance costs to be higher than necessary. A further assumption was that these problems could be reduced or eliminated by using diagnostic aid systems. Reducing the magnitude of the problems should lead, in turn, to a reduction in maintenance costs.

This report documents the methodology, several applications based on currently available data, and the results of our examination of Army land vehicle maintenance data and data sources.* It provides a more formal record of information gleaned from reports, interviews,

*Only automotive subsystems (those for which the U.S. Army Tank-Automotive Commands are responsible) are considered. Weapons, fire control, etc., are not addressed.

analyses, and impressions, previously reported only in a series of informal discussions and briefings. Although we believe this report presents a reasonably fair and accurate picture of Army vehicle maintenance data, it is by no means an exhaustive treatment or the last word on the subject. (Readers interested in only the data-related portions of this report should see Secs. V and VI.)

Problems that increase maintenance costs are of two types: those that increase the frequency of maintenance by decreasing vehicle reliability (manufacturing faults, improper operation/neglect, and maintenance-induced faults), and those that increase the cost (in parts and/or labor) of each maintenance action by decreasing vehicle maintainability (inefficient fault isolation, faulty malfunction diagnosis, late detection of faults, excessive rework, and low productivity). These problems can in turn be reduced by one or more of the functions performed by diagnostic aid systems (use monitoring, health monitoring, failure prediction, failing/failure detection, fault isolation, mechanic education, and repair verification). This general approach differs from the approach taken by other studies which were concerned with evaluation of one specific diagnostic aid system. In Sec. II we describe a scheme to evaluate diagnostic aid systems using a cost factor approach. Our Cost Savings Model (CSM), designed to implement our methodology, calculates the impact of diagnostic aids given estimates of current maintenance costs, problem magnitudes, and diagnostic effectiveness. The difference between current costs and costs if all problems are eliminated is a measure of the potential maximum benefit of diagnostic aids. If a vehicle seldom needs repair and is easy and cheap to fix, it is not a good

subject for a diagnostic aid system. Although the CSM is useful as a learning device and for parametric analyses, it is not completely satisfactory, since it works only with cost factors and at a very aggregate level.

Section III describes three models that were examined for possible application to a more comprehensive approach than that possible with the CSM. While each model did possess relevant features, they were too detailed or required too many data for our purposes. In addition, none of them could explicitly consider diagnosis. Therefore, we designed a new model, the Maintenance and Diagnostics Analysis Model (MADAM), using a reliability/maintainability approach. Up to six vehicle subsystems are described in terms of their reliability and maintainability characteristics; these characteristics are then modified by problems that typically occur in vehicle operating and maintenance environments. Maintenance costs can then be calculated with full problem contributions (the current situation), with no problem contributions (minimum maintenance costs), or with partial problem contributions (use of a diagnostic aid system). MADAM is calibrated to 1/4 ton truck (M151A1) maintenance using test data, field data, and subjective estimates where data are unavailable. The four calibration parameters are maintenance frequency, labor hours per maintenance action, parts cost per action, and vehicle availability. The calibrated base case is used to identify the most important maintenance problems, to examine the effects of changes in problem magnitudes, and to estimate the impacts of a diagnostic aid system. The most serious limitation of

this methodology is a lack of good data, which in turn makes a parametric approach necessary.

Data requirements of MADAM are discussed in Sec. IV; these fall into the general areas of reliability (frequency of repair), maintainability (costs to repair), maintenance problems, and diagnostic effectiveness. More specifically, MADAM requires the frequency of maintenance actions (by vehicle subsystem), the parts and labor expended per action, the types and magnitudes of problems that increase maintenance frequency or cost, and the effectiveness of diagnostic aid systems in reducing these problems. Data on unscheduled maintenance are available but often incomplete and inconsistent among different sources, making it necessary to use considerable subjective judgment. Scheduled maintenance requirements are undergoing examination and change; current requirements are quite specific, but data indicate that less scheduled maintenance is being performed than required. Other data, such as vehicle use profiles, are simply nonexistent.

Section V identifies and provides general background information on several sources--past, present, and future--of Army vehicle maintenance data. Sources of field data include TAERS (the Army Equipment Records System), TAMMS (the Army Maintenance Management System), SAMS (Standard Army Maintenance System), SDC (Sample Data Collection) and local collection efforts at post or unit level. The TAERS collection system, in use from 1962 to 1969, was an extensive but unsuccessful system--paperwork and costs were high, and data validity low. Use of the TAERS data base requires a considerable

additional data processing effort. TAMMS reduced the paperwork and costs somewhat, but data validity remains questionable. SAMS, now under development, is intended to standardize and simplify maintenance management, reporting, and data flows. SDC plans provide for gathering data on a selected sample of a vehicle type over a specified period of time; their cost and accuracy can vary greatly, depending on the number of vehicles, units, and sites, and the degree of control and unit support. Efforts at post/unit level are oriented primarily toward developing cost factors for use in a particular location and for limited purposes. Various test data are also available, but results may not be transferable to field conditions. Tests usually involve a single new vehicle, operated for a relatively short time at high daily mileage under close supervision. Test results can provide useful information, but must be interpreted carefully. Use of civilian commercial data (from trucking firms, taxi fleets, etc.) as an analog for Army experience is not advisable--even if data could be obtained in a common format, Army management objectives and constraints are so different from commercial practice that any results would be highly questionable. The MACRIT (Manpower Authorization Criteria) process, used in developing TO&E (Table of Organization and Equipment) maintenance personnel spaces, has enough well-known defects to make it a very questionable source of data. In our opinion, the Army's past data systems have expended too much effort on data processing and not enough on data requirements, collection techniques, and quality.

Vehicle maintenance data problems are discussed in more depth in Sec. VI. Army data sources and institutional knowledge are

fragmented, and there exist (as in most organizations) bureaucratic, organizational, and cost considerations that affect data collection efforts. Data problems are illustrated by comparisons of 1/4 ton truck (M151A1) maintenance data obtained from several sources. Significant variations are apparent among sources in total annual maintenance costs, maintenance costs per mile, and maintenance person-hours per 1000 miles. Differences by geographical area exist within the same source. The widest differences exist between those sources using a top-down approach (allocating all costs relating to vehicle maintenance, including some which may be essentially fixed, among the various vehicle types) and those using a bottom-up approach (adding up the costs of the various maintenance actions performed on vehicles). Some sources base labor requirements on MACRIT inputs--numbers that lack adequate justification. The potential impact of such variations is shown through a description of the procedures used in an Army cost-benefit study for a particular diagnostic aid system. The level of maintenance costs has a critical impact on any evaluation of diagnostic aids, since economic justification of these aids depends on their leverage on maintenance costs.

Section VII describes the present study's findings and conclusions. The methodology developed in the study and implemented in the CSM and MADAM models can be very useful in parameterizing the impacts of diagnostic aid systems on maintenance costs. Although existing data can serve as useful benchmarks for parametric analyses, it is apparent that no one knows with a reasonable degree of accuracy what it costs to maintain the various types of Army land vehicles.

II. THE COST SAVINGS MODEL--A COST FACTOR APPROACH

Proponents assert two principal benefits from the use of diagnostic aid systems in military vehicle maintenance: reductions in maintenance costs (both parts and labor),* and reductions in vehicle downtime. In this and the following section we discuss methods of estimating these benefits. This section considers only savings in maintenance costs; Sec. III adopts a more comprehensive approach that deals with both maintenance costs and vehicle availability. The work described in Sec. III is an evolutionary development from that in Sec. II and uses much of the same terminology. The CSM begins with estimates of current vehicle maintenance costs, calculates the proportions of these costs that are reducible by the use of diagnostic aid systems, and then calculates the potential savings. MADAM, described in Sec. III, begins with requirements for maintenance actions and then calculates the cost of performing these actions with and without diagnostic aid systems. Both approaches were designed with knowledge of the lack of accurate and detailed data on Army vehicle maintenance (discussed in Sec. V).

BACKGROUND

As we gathered information on the Army vehicle maintenance system, costs, and problem areas, and on diagnostic aid system

*Other cost savings are also possible. Engines kept in better tune should consume less fuel, fewer breakdowns should reduce the need for towing and maintenance float vehicles, reduced consumption of parts should allow reductions in parts inventory levels, and so on.

capabilities, the need for some scheme to combine these various factors in a consistent manner became apparent. Most of the initially available data were cost-oriented, leading us to develop a cost factor approach able to operate on these data and produce rough estimates of the potential impacts of diagnostic aid systems. At that point we were interested in gaining a better understanding of the problem, in identifying areas where more information was needed, and in examining possible areas of sensitivity.

This is not the first study to attempt to estimate the utility of diagnostic aid systems; others have taken different approaches, but all of them are basically cost-oriented. Previous work has been concerned primarily with particular diagnostic aid systems rather than with developing a generally applicable methodology. Authors of the earlier studies were all involved in one way or another with the diagnostic aid system being studied, whether as proponents, opponents, or developers.

Of the three principal analyses, Brachman's is the broadest in scope [1]. However, the report is often difficult to follow; in many instances, the derivation of numerical results is not shown. The Kruvand study is easier to follow, but much more limited in scope [2]. The only benefit examined in any detail is the savings in parts cost resulting from reduced replacement of "good" parts. Kruvand also considers the Army units in which the diagnostic equipment would be placed and concludes that very few units have enough vehicles to make the use of diagnostic equipment pay off. The most recent work is a joint effort by the Army's Tank-Automotive Command (TACOM) and

RCA, the proponent and contractor for the STE/ICE* diagnostic system [3]. This study is the best we have seen; it has the most complete set of data and is fairly easy to follow. Its only potential shortcoming is that some of the data (especially current maintenance costs) may be questionable, because of the generally poor quality and fragmentary nature of the Army's vehicle maintenance data.

The major shortcoming of these studies is that they evaluated a diagnostic aid system only from the limited standpoint of the system's ability to isolate faults (identifying the vehicle problem and isolating the faulty subsystem or component). As discussed below, diagnostic aid systems (even ones designed primarily for fault isolation) can also perform other potentially useful functions. For this reason, our approach is oriented around diagnostic functions (rather than particular diagnostic aid systems) and the ways in which these functions interact with and reduce maintenance problem areas.

MODEL DESIGN

Our approach is based on two assumptions: First, that current maintenance practices embody a number of problems that increase maintenance costs, and second, that the magnitudes of these problems can be reduced through the use of diagnostic aid systems. We first identified and characterized the problems that currently exist in land vehicle maintenance and the functions that diagnostic aid

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*Simplified Test Equipment/Internal Combustion Engine powered materiel. STE/ICE is a digital multimeter using either a transducer kit or a built-in diagnostic connector assembly, and is scheduled to become operational in the field in FY 1979.

systems might be capable of performing. We then specified the interactions between maintenance problems and diagnostic functions (which functions affect which problems), and developed the Cost Savings Model to apply the methodology. This section defines the maintenance problems and diagnostic functions, then provides an explanation and application of the CSM.

Maintenance Problems

Maintenance problems are of two general types--those that increase the frequency of maintenance actions and those that increase the cost (in parts and/or labor) of each action.* Manufacturing faults, improper operation/neglect, and maintenance-induced faults contribute to the frequency of maintenance; inefficient fault isolation, faulty malfunction diagnosis, late detection of faults, excessive rework, and low productivity contribute to the cost of maintenance. Each of these problems is defined and described in the following paragraphs.

Manufacturing faults are defects that result from improper manufacture or assembly** of new or rebuilt vehicles or parts, or from inadequate preparations for storage or removal from storage.

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*The problems are addressed here in the context of their manifestations rather than their basic causes. For example, improper vehicle operation may be a result of a more fundamental problem such as inadequate driver training.

**Poor design can also increase the frequency of maintenance. We assume that the design is fixed once the vehicle is provided to operating units, although diagnostic aid systems may provide useful information for new designs or product improvement programs.

Manufacturing faults increase the frequency of maintenance actions, and include such defects as bad filters or seals, loose or missing fasteners, poorly machined parts, and incorrect wiring.

Improper operation/neglect is any improper operation of the vehicle or neglect of critical checks by the operator or crew and also increases the frequency of maintenance. Typical abuses are operating the vehicle, engine, or transmission at excessive speeds or temperatures, and riding the clutch or brake. Examples of negligence are operating the vehicle with improper levels of oil, coolant, or electrolyte, or operating it with the emergency brake set.

Maintenance-induced faults are defects caused during maintenance. Such faults increase the frequency of maintenance. Examples are reversed electrical polarity, mechanical damage to parts, or failure to replace drain plugs when replacing oil or coolant.

Inefficient fault isolation is the use of improper procedures or test equipment, or poorly trained personnel, resulting in excessive time to locate and isolate faults. Since only time (not parts) is involved in fault isolation, the effect of inefficient fault isolation is to increase the labor expended in maintenance actions.

Faulty malfunction diagnosis is the incorrect diagnosis of a malfunction involving the replacement of good parts, and results from the often-used procedure of trial-and-error replacement. The impact of faulty malfunction diagnosis is on both parts and labor costs. Examples are replacing a battery when the malfunction is in the generator, replacing spark plugs or the carburetor when the timing is bad, or replacing the radiator when only the thermostat is bad.

Late detection is the failure to detect a fault, which becomes worse over time and/or causes secondary faults. Late detection affects both parts and labor costs and can necessitate more extensive maintenance than if the fault had been detected in its early stages. Examples are a failing generator which damages the electrical system, worn brake linings which lead to scoring of the brake drums, or a clogged air filter which allows dust ingestion to damage the engine.

Excessive rework is the need for additional maintenance caused by an improper initial repair. The impact of excessive rework is on both parts and labor costs. Examples are adjusting the timing to incorrect specifications, installing a brake wheel cylinder improperly allowing brake fluid to leak, etc.

Low productivity affects only labor costs and occurs when any maintenance action takes longer than necessary. Examples are taking excessive time to road test or to install and test parts.

These general problems, although they include the major contributors, may not cover every possible influence on vehicle maintenance frequency and costs. Table 1 summarizes the impact of the problems.

Diagnostic Functions

After the problems inherent within the maintenance system were identified, it became necessary to determine what diagnostic functions were possible and how they might affect the problems. We did not attempt to define particular diagnostic aid systems that could perform the functions; that task is being addressed as another

Table 1

AREAS OF IMPACT OF MAINTENANCE PROBLEMS

On the Frequency of Maintenance

- Manufacturing faults
- Improper operation/neglect
- Maintenance-induced faults

On the Cost of Maintenance

Parts

- Faulty malfunction diagnosis
- Late detection
- Excessive rework

Labor

- Faulty malfunction diagnosis
- Late detection
- Excessive rework
- Inefficient fault isolation
- Low productivity

part of the Rand study. General definitions of the diagnostic functions are provided below.

Use monitoring allows observation of the ways that the vehicle is operated. It records vehicle/driver and vehicle/environment interactions (hours of operation, number of starts and stops, excessive speeds or temperatures, etc.). Results provide information on vehicle duty cycles and on improper operation/neglect.

Health monitoring allows observation of the basic performance or soundness of critical components or subsystems of the vehicle. It might be used to check vehicles prior to dispatch and to detect any manufacturing faults.

Failure prediction permits the measurement of subsystem or component use, and estimates its useful life remaining before maintenance is required. Failure prediction estimates reliability so that maintenance can be performed before faults occur or before secondary faults result.*

Failing/failure detection indicates whether the vehicle should be driven by displaying warnings of dangerous conditions such as low fluid levels or clogged filters. It could also be used to trigger maintenance before faults occur or cause secondary faults.

Fault isolation provides faster and more accurate identification of faulty parts by locating and isolating the component causing the malfunction, reducing the chances of replacing the wrong part and the time spent locating faults.

Mechanic education provides training to increase the capability and efficiency of the mechanic, reducing maintenance time.

Repair verification checks that proper maintenance and repair have been correctly performed, reducing the number of jobs that must be redone and detecting any additional faults caused by maintenance actions.

Each of these diagnostic functions is capable of reducing the severity of one or more maintenance problems. For example, the fault isolation function has an impact on two problems: It enables fault isolation procedures to be performed more efficiently and also

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*One body of opinion holds that failure prediction is seldom useful--that in most cases maintenance should not be performed until the subsystem or component fails or gives evidence of impending failure.

indicates which components require either repair or replacement, thus reducing faulty malfunction diagnosis. Repair verification indicates if faults have been induced during maintenance, and also verifies that the fault requiring remedial action has been properly corrected, assuring that no rework is necessary. A summary of the assumed interactions is shown in Table 2.

Table 2

ASSUMED PROBLEM-FUNCTION INTERACTIONS[a]

Maintenance Problems	Diagnostic Functions[b]						
	Use Monitoring	Health Monitoring	Failure Prediction	Failing/ Failure Detection	Fault Isolation	Mechanic Education	Repair Verification
Manufacturing faults		X					
Improper operation/ neglect	X						
Maintenance-induced faults							X
Inefficient fault isolation					X		
Faulty malfunction diagnosis					X		
Late detection			X	X			
Excessive rework							X
Low productivity						X	

[a]These interactions are *illustrative only; many others are possible*. For example, mechanic education may also reduce inefficient fault isolation and maintenance-induced faults in addition to increasing productivity.

[b]A given diagnostic aid system may perform more than one function.

CSM Procedures

The general flow of the CSM is illustrated in Fig. 1. Inputs include current annual maintenance costs, problem areas and impacts,

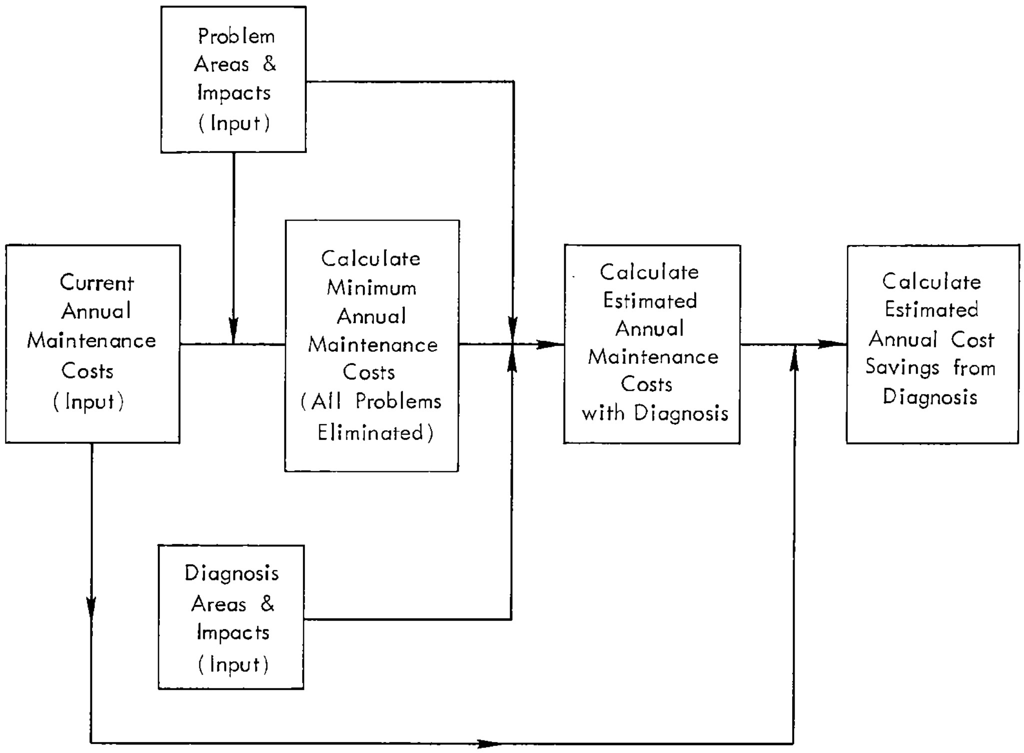

Fig. 1 — Flow of Cost Savings Model

and diagnosis areas and impacts. Once current annual costs and problem magnitudes are known or assumed, minimum annual costs (i.e. the costs with all problems eliminated) are calculated.* Then, since the diagnosis areas and impacts are also known, the estimated annual costs (assuming the use of diagnosis) can be calculated. These are

*The difference between these minimum costs and the input current costs is a measure of the potential leverage for diagnosis. A vehicle that seldom needs repairs and is easy and cheap to fix is not a good candidate for diagnostic aids. Most military equipment is not in this category.

compared to the input annual costs to estimate the savings achievable by using diagnostic aids.*

A simple example will illustrate the CSM procedures.** Suppose that maintenance of some subsystem of each vehicle of a given type uses \$100 worth of parts each year, and that faulty malfunction diagnosis increases minimum parts costs 30 percent and rework 10 percent. We assume that

$$\begin{bmatrix} \text{CURRENT} \\ \text{ANNUAL} \\ \text{MAINTENANCE} \\ \text{COSTS} \end{bmatrix} = \begin{bmatrix} \text{MINIMUM} \\ \text{ANNUAL} \\ \text{MAINTENANCE} \\ \text{COSTS} \end{bmatrix} (1 + f_1)(1 + f_2) \ldots (1 + f_n)$$

where f_i is the magnitude of problem i without diagnosis. Then

$$\$100 = \begin{bmatrix} \text{MINIMUM} \\ \text{ANNUAL} \\ \text{PARTS} \\ \text{COSTS} \end{bmatrix} (1 + 0.30)(1 + 0.10) \ ,$$

$$\begin{bmatrix} \text{MINIMUM} \\ \text{ANNUAL} \\ \text{PARTS} \\ \text{COSTS} \end{bmatrix} = \$70 \ ,$$

---

*These savings can in turn be compared to the acquisition and support costs of the aids to determine if the use of diagnosis is worthwhile. A factor not considered by the CSM is vehicle availability, which is critical in wartime. Cost savings may not be feasible if they would seriously reduce wartime availability. On the other hand, use of a diagnostic aid system might so improve wartime availability that its implementation could be justified on this basis alone.

**We have selected a multiplicative representation for the CSM. Our approach was to keep the model as simple as possible while still representing reality reasonably well. Arguments could be made in favor of other functional forms (additive or combinations of additive and multiplicative), but in the absence of validating data we believe that attempts at refinement can only be speculative, and a simple multiplicative form is adequate.

and the maximum potential leverage is \$100 - \$70 = \$30 per year per vehicle in parts costs. Suppose further that a diagnostic aid system is proposed that will isolate faults and improve the faulty malfunction diagnosis rate by 20 percent, but will not affect the rework rate. If

$$f'_i = \text{magnitude of problem } i \text{ with diagnosis}$$

$$= f_i\ (1 - \text{improvement}),\ \text{then}$$

$$f'_1 = 0.30\ (1 - 0.20) = 0.24$$

$$f'_2 = 0.10\ (1 - 0.0) = 0.10$$

and, since

$$\begin{bmatrix} \text{ESTIMATED} \\ \text{ANNUAL} \\ \text{PARTS} \\ \text{COSTS WITH} \\ \text{DIAGNOSIS} \end{bmatrix} = \begin{bmatrix} \text{MINIMUM} \\ \text{ANNUAL} \\ \text{PARTS} \\ \text{COSTS} \end{bmatrix} (1 + f'_1)(1 + f'_2)\ \ldots\ (1 + f'_n)\ ,$$

$$\begin{bmatrix} \text{ESTIMATED} \\ \text{ANNUAL} \\ \text{PARTS} \\ \text{COSTS WITH} \\ \text{DIAGNOSIS} \end{bmatrix} = (\$70)(1 + 0.24)(1 + 0.10) = \$95\ ,$$

and the savings in parts costs achievable by using the fault isolation aid = \$100 - \$95 = \$5 per vehicle per year.

As we pointed out earlier, several factors can increase the potential benefits of diagnostic aid systems. For example, if the vehicle subsystem consumes \$1000 worth of parts every year (rather

than \$100 worth), then the fault isolation aid can save \$50 per vehicle. Alternatively, if the faulty malfunction diagnosis rate is 50 percent (rather than 30 percent), and the aid will improve this by 40 percent (rather than by 20 percent), the aid can save \$13 per vehicle. These effects are illustrated in the following example, which uses actual data.

SAMPLE CSM APPLICATION

Table 3 shows estimates of current annual maintenance costs for four Army vehicle types. Two factors that affect the savings achievable with diagnostic aid systems are the magnitudes of any maintenance problems and the degree of improvement possible with

Table 3

CURRENT ANNUAL MAINTENANCE COSTS PER VEHICLE
(In FY 1975 dollars)

Vehicle Type	Number of Vehicles	Annual Maintenance Cost (\$)		
		Parts	Labor	Total
1/4 ton truck	46,120	360	1072	1432
2-1/2 ton truck	53,720	253	1205	1458
APC[a]	9,282	1754	1972	3726
Tank	4,238	5685	1978	7663
	113,360			

SOURCES: Number of vehicles from Ref. 3; cost data were supplied during personal communication with Harry Douglas of TACOM, February 13, 1976. The cost data were adjusted to FY 1975 dollars (see Secs. V and VI for a detailed discussion of data and sources).

[a]Armored personnel carrier.

diagnosis. The STE/ICE study [3] estimates both these factors; these estimates were adjusted to conform to the CSM format and were used in calculating a base case. Three excursions from this base case were made: Improvements from diagnosis were increased 50 percent, problems were increased 50 percent, and both improvements and problems were increased 50 percent. The results are shown in Fig. 2. Annual savings for the assumed vehicle fleet in the base case are $8 million, compared to a maximum possible savings of $47 million. When both problems and improvements are increased 50 percent, these results increase to $14 million and $57 million, respectively.

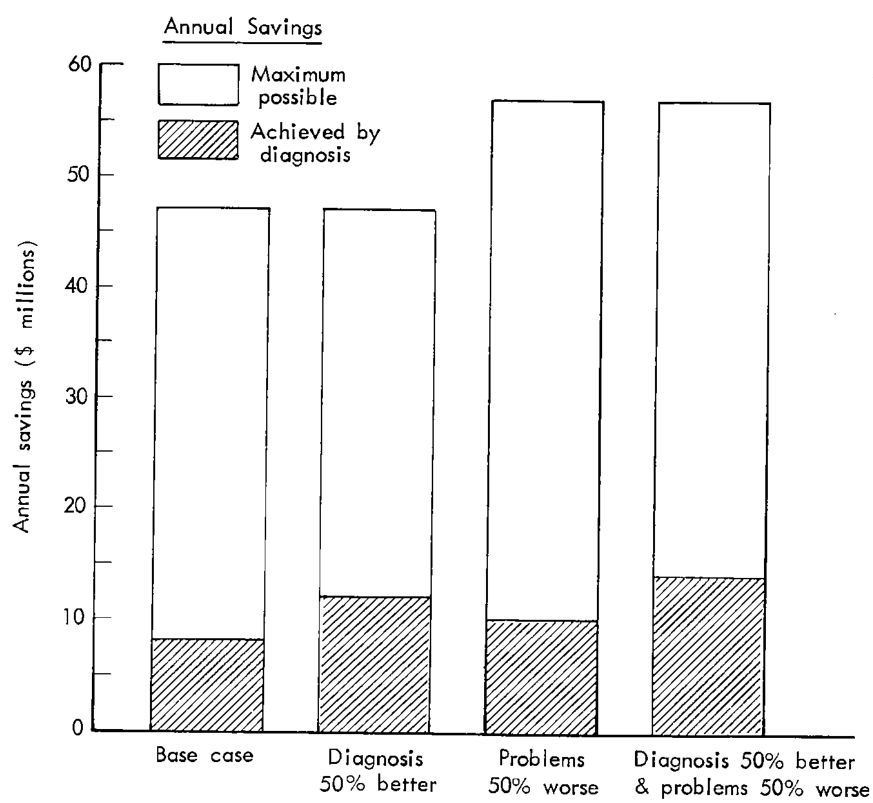

Fig. 2—Applications of Cost Savings Model

Comparing the two intermediate cases, increasing improvements 50 percent resulted in $2 million more savings than when problems were increased 50 percent. In addition to the effects shown here, the impact of diagnosis, of course, depends on fleet size and current maintenance costs (Table 3). Estimates of current maintenance costs can vary considerably from source to source, as discussed in Sec. VI.

Although the CSM was useful for parametric analyses and for highlighting the kinds of effects shown in Fig. 2, it was not completely satisfactory. Since the CSM works only with cost factors and at a macro level, estimating the necessary parameters (problem magnitudes and diagnostic improvements) can be quite difficult--those who are knowledgeable about maintenance problems at the mechanic level are usually unfamiliar with costs. When cost estimates can be located, they are typically very aggregated and embody many hidden assumptions regarding pay rates, inflation, overhead, and so on. Vehicle maintenance breaks down conveniently by vehicle subsystem (fuel, electrical, etc.)--each with its own problems and degree of susceptibility to diagnostic aids--but the CSM does not operate at the subsystem level. In essence, the CSM takes an aggregated number (current costs without diagnosis), breaks it down, eliminates problems to obtain minimum costs, estimates diagnostic aid impacts, and then re-aggregates to estimate annual costs with diagnosis. This is a tortuous process made necessary by a lack of good data and is difficult to relate to the actual physical processes of vehicle breakdowns and repairs. The CSM was used mainly as a heuristic

device while attempting to locate and obtain some existing model that would better meet our needs. Since no other model fit the requirements, we designed MADAM, described in Sec. III.

III. THE MAINTENANCE AND DIAGNOSTICS ANALYSIS MODEL-- A RELIABILITY/MAINTAINABILITY APPROACH

The magnitude of the maintenance costs for Army land vehicles depends on a number of factors, such as vehicle age, type, and conditions of use, as well as on the frequency and resources associated with each maintenance action. To measure the impact of diagnostic aid systems on maintenance costs, it is essential to understand the vehicle environment and the variables within it.

The Cost Savings Model, beginning with current costs, was designed to calculate minimum costs and then the savings that could be realized through use of diagnostic aid systems. Although the model proved a useful tool, it could not fully describe the impacts of maintenance problems on maintenance costs. It was apparent that the capabilities of the cost model needed to be expanded, by either obtaining or designing a model that, through adequate description of present maintenance costs, would parametrically determine the possible cost savings from the use of diagnostic aid systems. "Current" costs, in this case, would be a calculated output as opposed to a known input as in the Cost Savings Model. In effect, the desired approach was to determine current maintenance costs with and without diagnostic aid systems.

It soon became obvious that a great deal of effort had been expended in attempts to estimate maintenance costs by "simulating" the Army maintenance system. In our attempts to identify a model that either already could examine the effects of diagnostic aid

systems on maintenance or could easily be modified to do so, we examined several different types of models. Three of the most significant are discussed below.

OTHER MODELS

MAWLOGS (Models of the U.S. Army Worldwide Logistics Systems) is representative of the set of models that attempt to simulate the logistics system in a very detailed way. MAWLOGS is not simply a single model but a system for constructing models. Its purpose is to integrate the supply, transportation, and maintenance functions through a multilevel system in a single discrete-event stochastic simulation. MAWLOGS is composed of a large number of "modules," each of which represents an activity or logistic function. Any subset of the modules may be linked to form a configuration specified by the user. The simulation is extremely complex and requires a large amount of computer time. A team of analysts at the U.S. Army Logistics Center is responsible for adapting MAWLOGS to Army needs. MAWLOGS has been utilized in several studies since its development; Ref. 4 is one example.

There are many factors that militated against use of MAWLOGS for our purposes. Our primary objective was to study the impacts of diagnostic aid systems on maintenance activities and costs. Although MAWLOGS does contain maintenance modules, and its proponents claim it can examine diagnosis, this is in fact not the case. MAWLOGS currently addresses "diagnosis" only in the sense of fault isolation--by choosing the type of fault from a distribution. Thus,

it would have been necessary to design additional modules to simulate diagnostic functions if we were to utilize MAWLOGS. We considered the time required to accomplish this excessive. In addition, the expense of computer time to perform several comparative analyses using MAWLOGS seemed prohibitive.

The RMC (Resource Management Corporation) model represents a simpler, less detailed class of models that do not attempt to describe every facet of the logistics or maintenance system in detail. It was designed to determine the operating and maintenance costs that would result from the reliability and maintainability goals of the Main Battle Tank (MBT-70) [5]. Based on a Monte Carlo technique, the model simulates events through the selection of random numbers, given historical failure and repair distributions.

The RMC model is simple and straightforward, and although it does not deal directly with diagnosis, we felt that such a capability could be incorporated with minimal effort. However, we were unsuccessful in our attempts to obtain the model in its original form.*

The TCM LCC (Teledyne-Continental Motors Life Cycle Cost) model, like the RMC model, is of the simpler variety. It determines, among other things, the labor and parts costs associated with scheduled and unscheduled maintenance as well as overhaul, assuming an average failure rate for the entire fleet. The complete model actually comprises three separate programs: the subsystem data preparation program, the main life cycle cost program, and a

*The current form of this model bears little relationship to the original; it has been expanded to such a degree that it can no longer be considered simple.

print/plot/post-processing program. The main purpose of the first program is to reduce TAERS and/or other similar types of data to a form useful for determining the distributions for the fleet failure rates. One advantage of the LCC model is that it has no need to choose random numbers for its failures. This, of course, pre-supposes that the data used in the data reduction routine are complete and correct. The LCC model is relatively simple and Teledyne has found several applications for it [6,7].

None of the models we encountered, including the three described above, could specifically examine the impacts of diagnostic aid systems on maintenance costs. Although we obtained the Teledyne model, and therefore had the option of adapting it to address this issue, we chose not to attempt it. The reason for our decision lies in the quality and quantity of the data used by Teledyne in its data reduction routine. TAERS data for the four vehicles we wished to examine are not always readily available and are of questionable validity.* In addition, reducing the data to a form we could use would probably have involved the design of a routine more complicated than the simulation itself.

MADAM METHODOLOGY

These factors, then, led to the decision to formulate a methodology based on the use of diagnostic aid system considerations and to implement this methodology through the design of a new model.

*Under TAERS, every maintenance action ever performed was to be entered on forms for subsequent addition to a massive data base. There was essentially no monitoring of accuracy. Further description of TAERS can be found in Sec. V.

The resulting model is called MADAM, an acronym for Maintenance and Diagnostics Analysis Model, and is of the simpler RMC-Teledyne type. One form of MADAM is similar to the RMC model in that it uses random numbers to generate both requirements for maintenance actions and maintenance costs. Each random number is chosen from either a reliability or a maintainability distribution constructed using estimates and any available data. Another form of the model uses a simple direct calculational procedure to determine when an unscheduled maintenance action is performed and the resources required for the repair; this latter form was used to calibrate MADAM to current costs. Scheduled maintenance is considered to be performed at prescribed intervals* in both forms of MADAM. MADAM uses essentially the same basic methodology as the Cost Savings Model; the maintenance problems and their effects are as defined in Sec. II.

MADAM is designed to handle unscheduled maintenance actions in up to six vehicle subsystems. For initial application, all six subsystems of the 1/4 ton truck (excluding the body) are processed. (The subsystem breakdown was the same as in the maintenance allocation chart, a condensed form of which is shown in Table 4.) However, the model is capable of handling any reasonable number of subsystems.

The costs of scheduled maintenance actions are determined by the frequency with which maintenance is performed and the resources

*The 1/4 ton truck requires preventive maintenance at 1000 mile intervals, semiannually and annually.

Table 4

LEVEL OF MAINTENANCE FOR VEHICLE SUBSYSTEMS
OF THE 1/4 TON TRUCK

Subsystem	Maintenance Level	
	Parts Replacement	Parts Repair
Engine		
Block assembly	Direct support	General support
Oil pump	Direct support	Direct support
Fuel		
Carburetor	Organizational	Direct support
Fuel pump	Organizational	Direct support
Electrical		
Generator	Organizational	Direct support
Starter	Organizational	Direct support
Distributor	Organizational	Organizational
Batteries	Organizational	--
Cooling		
Radiator	Organizational	Direct support
Water pump	Organizational	--
Transmission/Drive Train		
Clutch assembly	Direct support	--
Transmission/transfer	Direct support	General support
Propeller shafts	Organizational	Organizational
Differentials and axles	Organizational	General support
Brakes/Suspension		
Brakes, shoes, and linings	Organizational	--
Master cylinder	Organizational	--
Wheel cylinders	Organizational	--
Suspension assembly	Organizational	Organizational
Wheels and tires	Organizational	Organizational
Steering assembly	Direct support	--
Springs and shock absorbers	Organizational	--

necessary to execute required maintenance actions.* The costs involved in unscheduled maintenance are determined by two main influences: the reliability, described by the frequency of malfunction, and the maintainability, a function of the parts requirements and repair times.

In MADAM, some maintenance problems contribute to degree of reliability or frequency of unscheduled maintenance, and some contribute to level of maintainability, or amount of resources required by unscheduled maintenance. The resources used in a repair action may be affected by any or all of the following maintenance problems: inefficient fault isolation, faulty malfunction diagnosis, late detection of faults, excessive rework, and low productivity. Frequency of repair is influenced by three of the problems: manufacturing faults, improper operation/neglect, and maintenance-induced faults from both scheduled maintenance actions and previous unscheduled actions. (The more often maintenance is performed, the greater the possibility that a maintenance-induced fault will result.)

A summary of the general capabilities of the model is as follows:

Given:

- o A vehicle with one to six subsystems
- o The total number of miles or hours the vehicle is to be operated

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*Scheduled maintenance, although it is accounted for in MADAM, will not be further discussed here. The calibration section presents a detailed description of its treatment.

- The frequency and resources of scheduled maintenance actions
- Distributions for each subsystem describing
  - the frequency of unscheduled maintenance actions (the reliability)
  - the labor (person-hours) required for each action (the maintainability)
  - the parts required for each action (the maintainability)
- Magnitudes of the problems which are believed to influence the frequency, labor, and parts requirements of unscheduled maintenance actions
- Magnitudes of diagnostic functions which are believed to have an impact on these problems

The model determines:

- The time (in hours) or distance (in miles) at which each maintenance action is required (by subsystem)
- The labor and parts required for each of these actions
- The total maintenance costs over the miles or hours of operation of the vehicle
- A measure of the availability of the vehicle

This methodology is discussed in more detail in the subsections to follow. They include a description of the model with respect to reliability, maintainability, diagnostic aid system impacts, and availability. The final subsection discusses the procedure used to calibrate the model to current maintenance costs.

Reliability

To describe the frequency of repair of a given subsystem, the Weibull distribution was chosen. It has the following form:

$$F(t) = 1 - \exp(-t^B/A) \tag{1}$$

where

$F(t)$ is the cumulative probability of an unscheduled maintenance action (cumulative density function).

B is a shape parameter.

A is the mean miles or hours between unscheduled maintenance actions.

The reliability, $R(t)$, of a subsystem is defined as

$$R(t) = 1 - F(t) \tag{2}$$

The simple rate of occurrence of unscheduled maintenance actions may then be written

$$Z(t) = \frac{-R'(t)}{R(t)} = \frac{B}{A} t^{B-1} \tag{3}$$

where $R(t)$ is the reliability and $R'(t)$ is its derivative with respect to time.

Malfunction rate over time for most subsystems is generally described by the "bathtub curve" shown in Fig. 3. When the vehicle is very new or very old, it tends to require a large number of unscheduled maintenance actions, as is evidenced by the "tails" of the curve. However, for the largest portion of its lifetime, the vehicle requires maintenance at a roughly constant rate. This portion is indicated by the area enclosed by dotted lines in Fig 3. If B is set equal to 1 in Eq. (3), $Z(t)$ then describes a constant rate, inversely proportional to the mean time between unscheduled maintenance actions.

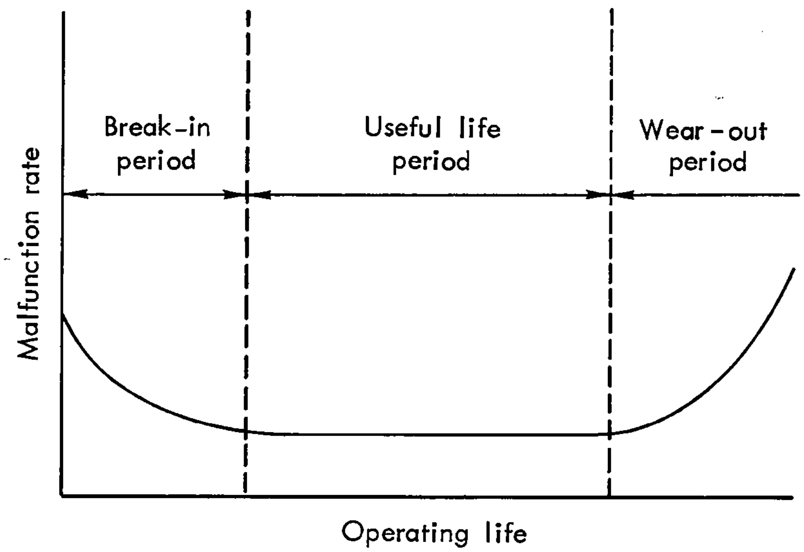

Fig. 3 — Malfunction rate over time

There is evidence that this rate is not constant over time for some subsystems [5]. In this case, B has a value different from 1. If, for example, B is set equal to 2, then Z(t) for the subsystem is increasing linearly over time.

In MADAM, the time of occurrence of an unscheduled maintenance action for a subsystem is calculated from Eq. (1). Given an "A," the mean time (or distance) between unscheduled maintenance actions in hours (or miles), and B, the shape parameter, a "t" is calculated, based on a randomly determined F(t). F(t), the cumulative probability, is a random number between 0 and 0.9999, chosen from a distribution of the form of Fig. 4. Each subsystem may require different values for the "A" and "B" parameters.

Before the distribution can be used to determine the time of occurrence of a maintenance action, it must be modified to account

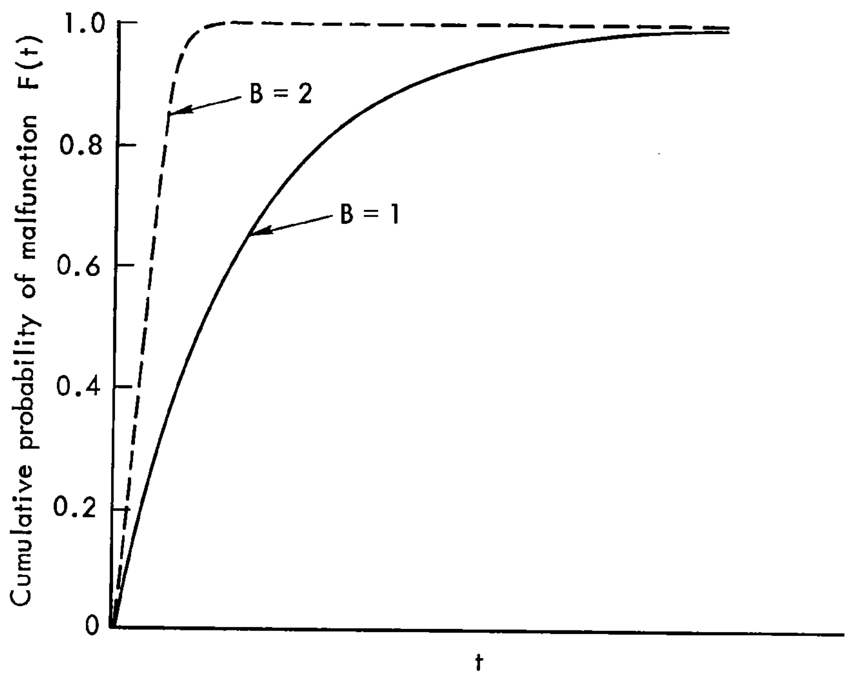

Fig. 4—Forms of F(t) distribution

for the vehicle's operating and maintenance environment. This is accomplished by incorporating the effects of maintenance and operating problems into the distribution; the three problems that influence the frequency of malfunction are manufacturing faults, improper operation/neglect, and maintenance-induced faults resulting from previous maintenance actions.

The degree to which a vehicle experiences these problems is reflected in a shorter mean time between unscheduled maintenance actions. This situation may be expressed by a modification in "A" as follows:

$$A_{actual} = A_{ideal} (1 - P_1)(1 - P_2) \dots (1 - P_n)$$

where

A_{ideal} is the mean time between actions under ideal operating conditions.

A_{actual} is the mean time between actions for a vehicle that experiences one or more of the possible problems.

P_i are numbers that reflect the magnitude of problem i ($0 \leq P_i < 1$).

If any of the problems is allowed to contribute, it is apparent that A_{actual} will be less than A_{ideal}. Thus, the subsystem will experience a malfunction at an earlier time than if it operated in an environment free of problems.

In the model, the first time an unscheduled maintenance action on a subsystem is required, the effect of maintenance-induced faults from other unscheduled maintenance actions is not incorporated. However, if scheduled maintenance resulting in maintenance-induced faults had been performed prior to this action, the effect is accounted for. Any subsequent unscheduled maintenance actions allow for the effect of maintenance-induced faults from both scheduled maintenance and any previous unscheduled maintenance. In addition, it is assumed that, after performance of unscheduled maintenance, the subsystem is returned to its original operating condition. In certain cases, this assumption may not be valid (e.g., a rebuilt subsystem may malfunction sooner than the original subsystem). Thus, for each subsystem, the model generates all unscheduled maintenance actions that occur within the operating period specified by the user.

Maintainability

When a subsystem malfunctions, MADAM assumes that the vehicle requires unscheduled maintenance. To determine the maintenance person-hours and parts cost involved in any repair action, the model uses simple exponential distributions. Equations (4) and (5) give the form of the person-hours and parts cost distributions, respectively:

$$F(PH) = 1 - \exp(-PH/C) \tag{4}$$

where

F(PH) is the person-hours cumulative density function.

C is the reciprocal of the mean service rate, where service rate is expressed as repair capability per person-hour.

PH is the number of person-hours required to accomplish the unscheduled maintenance action.

$$F(PC) = 1 - \exp(-PC/E) \tag{5}$$

where

F(PC) is the parts cost cumulative density function.

E is the reciprocal of the mean service rate, where service rate is expressed as repair capability per dollar of parts cost.

PC is the parts cost required to accomplish the unscheduled maintenance action.

The model determines then, for each unscheduled maintenance action, the associated person hours (PH) and parts cost (PC) by randomly choosing numbers between 0 and 0.9999 for F(PH) and F(PC),

respectively, and using the appropriate input distribution that has been specified by estimates of C and E, the reciprocals of the mean service rates. Total cost for the maintenance action is simply the sum of the person-hours* multiplied by the labor rate, plus the parts cost.

The person-hours and parts cost distributions that describe maintainability are also modified in the model by the effects of problems experienced by the subsystem once it requires maintenance.** In the case of Eq. (4), the problems increase the person-hours required for the maintenance action. This is reflected in the model by a decrease in the mean service rate (1/C). That is,

$$(1/C_{actual}) = (1/C_{ideal})(1 - P_1)(1 - P_2) \ldots (1 - P_r)$$

where

$1/C_{ideal}$ is the service rate under ideal maintenance conditions.

P_j is the magnitude of problem j that affects the labor required for the maintenance actions ($0 \leq P_j < 1$).

The contribution of the problems to the parts costs is similar. That is, the more severe the problem, the higher the cost. In Eq. (5), then, 1/E, the repair capability per dollar of parts cost, is decreased by the problem influence.

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*Additional person-hours might be needed to meet wartime needs or peacetime peak demands.

**As with the CSM, MADAM uses a multiplicative functional representation. The same reservations about its applicability apply here as in the CSM section (see the footnote, p. 17).

$$(1/E_{actual}) = (1/E_{ideal})(1 - P_1)(1 - P_2) \ldots (1 - P_m)$$

where $1/E_{actual}$ and $1/E_{ideal}$ reflect the service rate with and without the influence of problems and P_k is the magnitude of problem k that affects the parts cost. Thus, each time a subsystem requires maintenance, the model determines the person-hours, labor cost, parts cost, and total cost associated with the necessary repair action, assuming given problem magnitudes.

Impacts of Diagnostic Aid Systems

The effects of diagnostic aid systems on the reliability and maintainability of a subsystem can also be examined within the model. Each of the contributing problems may be ameliorated by the application of one or more of the diagnostic functions. For example, a fault isolation technique might reduce both inefficient fault isolation and faulty malfunction diagnosis. Diagnostic effects are incorporated within MADAM by decreasing the magnitude(s) of given problem(s), as follows:

$$P_{id} = P_i (1 - F)$$

where P_i and P_{id} are the magnitudes of a given problem without and with diagnostic functions, respectively, and F is the magnitude of the improvement due to the diagnostic functions ($0 \leq F \leq 1$).

A value of 1 for F signifies perfect diagnostic effectiveness 100 percent of the time it is applied. More reasonable values for F would, of course, be less than 1, reflecting limited diagnostic

applicability. That is, a given diagnostic function may have an impact on a particular problem for only a percentage of the total time the problem occurs and possibly with only limited effectiveness. For example, a diagnostic aid system might perform fault isolation 20 percent better than current procedures. This would therefore cause the magnitude of inefficient fault isolation to be only 80 percent as severe as it was without use of the system. Parametric estimates of the cost savings attributable to use of diagnostic aid systems can be obtained by estimating the impacts on maintenance problems.

Availability

In addition to the costs related to maintenance, the model calculates a measure of vehicle availability. However, unlike other definitions of availability, which incorporate time spent waiting for parts and vehicle transportation time, this definition (sometimes called inherent availability) considers only downtime during actual maintenance.

$$A = \frac{\mathrm{MMBMA}}{\mathrm{MMBMA} + \mathrm{MTTR}}$$

where MMBMA is the mean miles between maintenance actions (both scheduled and unscheduled) and MTTR is the mean time to repair. MTTR is converted to miles to preserve dimensional consistency by assuming 1.8 maintenance person-hours per clock hour and an average vehicle speed of 20 miles per hour. It is apparent that A is simply the ratio of operating time to total time (defined as operating time plus

maintenance time); it provides a measure other than cost of the impact of diagnostic aid systems on Army maintenance. Availability is most critical in wartime, and cost savings may not be feasible if they adversely affect wartime availability. On the other hand, improvements in availability might be sufficient by themselves to justify implementation of a diagnostic aid system.

Output

Output from MADAM is provided in the appendix. The first page lists reliability and maintainability parameters that are input for each of the subsystems. The second and third pages show the magnitudes of both the problems and the diagnostic factors that are input for each subsystem. The fourth page lists the scheduled maintenance inputs. The next six pages show (for each subsystem) the mileage at which each unscheduled maintenance action occurs, and the associated labor and parts costs. These numbers have been generated by the model and are outputs. The final pages summarize the outputs. All unscheduled maintenance actions are ordered with respect to their time of occurrence. A cumulative accounting of person-hours, labor cost, parts cost, and total cost is also provided. Finally, some summary parameters for unscheduled maintenance, including annual costs, are specified. The scheduled maintenance summary, similar to that for unscheduled maintenance, is then listed. The last page summarizes total costs for all maintenance actions. The numbers appearing in the sample output are representative of the "base case," which will be described in detail in the following discussion.

CALIBRATING MADAM

MADAM is presently calibrated to current estimates of maintenance costs for the 1/4 ton truck (M151A1). Three separate data sources were used for calibration purposes: U.S. Army Armor and Engineer Board (ARENBD) Initial Production Test data [8], U.S. Army Materiel Systems Analysis Activity (AMSAA) TAERS data [9], and U.S. Army Maintenance Management Center (MMC) Sample Data Collection (SDC) plan data [10].

The ARENBD test data detail the maintenance actions performed on a single 1/4 ton truck driven 20,000 miles over a period of 6 months. Naturally, these data are not representative of the maintenance a 1/4 ton truck in the field would require. Test conditions (short time period, high mileage) differ from field conditions. In addition, maintenance is performed during the test by mechanics who are probably more skilled than those in the field. It was thought, however, that the test data could at least provide an optimistic (as compared to the field) case for calibration. The AMSAA study [9] was done to determine the useful life of the 1/4 ton truck. It contains a large amount of field operations data (taken from TAERS), which was useful for the calibration. The third source of data which, like TAERS data, are collected in the field, is SDC. The SDC program was instituted in 1972 after the end of TAERS. It considers, as the name implies, only a selected sample of vehicles whereas the TAERS data include all vehicles.* Thus, three sources--one field-test-related and two field-operations-related--were used in the calibration of the

*See Sec. V for a more complete discussion of data sources.

model. As far as can be determined, there exist no additional sources that are detailed enough to provide the required information.

The calibration was accomplished by the direct calculational form of MADAM, which is illustrated in Table 5. Different notation for the calibration section has been deliberately adopted to avoid confusion with respect to the two different forms of the model. The outputs necessary to verify the calibration to known values are the frequency of maintenance actions (for both scheduled and unscheduled maintenance) and the person-hours and parts costs associated with each action. The equations used in the model to calculate these three basic parameters are shown in Table 5. Initial estimates of MADAM inputs were developed through discussions with Richard Salter of Rand; these inputs were then adjusted until MADAM outputs were in reasonable agreement with data obtained from Army sources.

Unscheduled Maintenance

The 1/4 ton truck was presumed to have the six major subsystems shown in Table 4. To determine the frequency of maintenance actions, we first estimated the mean miles between unscheduled maintenance actions (T_o in Table 5) for each of the six subsystems. The T_o that was used as input to the model was considered to be the mean miles between unscheduled maintenance actions that would apply under ideal conditions (i.e., with no problems contributing). The second step was to estimate the magnitudes of the problems that cause a higher-than-necessary frequency of unscheduled maintenance actions (the M_i in Table 5).

Table 5

MAINTENANCE AND DIAGNOSTICS ANALYSIS MODEL CALCULATIONS

$$T_{actual} = \left[T_o \prod_i [1 - M_i(1 - D_i)]\right]^{\frac{1}{B}} \quad (1)$$

T_{actual} = Mean miles between unscheduled maintenance actions (with problem contributions).

T_o = Mean miles between unscheduled maintenance actions (without problem contributions).

M_i = Magnitudes of the problems that influence the frequency of unscheduled maintenance actions.

D_i = Magnitudes of the diagnostic functions that impact on these problems.

B = Shape parameter (assumed to be 1.0 for calibration purposes).

$$L_{actual} = L_o / \prod_j [1 - M_j(1 - D_j)] \quad (2)$$

L_{actual} = Mean person-hours per unscheduled maintenance action (with problem contributions).

L_o = Mean person-hours per unscheduled maintenance action (without problem contributions).

M_j = Magnitudes of the problems that influence the labor requirements for unscheduled maintenance actions.

D_j = Magnitudes of the diagnostic functions that impact on these problems.

$$P_{actual} = P_o / \prod_k [1 - M_k(1 - D_k)] \quad (3)$$

P_{actual} = Mean parts cost per unscheduled maintenance action (with problem contributions).

P_o = Mean parts cost per unscheduled maintenance action (without problem contributions).

M_k = Magnitudes of the problems that influence the parts requirements for unscheduled maintenance actions.

D_k = Magnitudes of the diagnostic functions that impact on these problems.

Using the estimated values for T_o and the M_i (in this case, i = 1, 2, 3), a value for T_{actual} can be calculated according to Eq. (1) in Table 5 for each subsystem. Since the calculation is for calibration purposes, the diagnostic function contributions (D_i in Table 5) have been set equal to zero.

The estimates for T_o and M_1, M_2, and M_3 are shown in Table 6 for the six subsystems. The method used to assign these values relied heavily on judgment; this procedure was necessitated by the lack of data. Although some data on actual frequency of maintenance actions do exist for the 1/4 ton truck in mileage terms, no data exist for any time-related measure (such as operating hours or age). Thus, to calibrate to the existing data, the values for T_o were estimated in miles. The problems were then allowed to impact on T_o according to the first equation in Table 5 and the actual mean miles

Table 6

MEAN MILES BETWEEN UNSCHEDULED MAINTENANCE ACTIONS--MADAM INPUTS

Subsystem	No Problems (T_o)[a]	Problem Magnitudes (M_i)		
		Manufacturing Faults (M_1)	Improper Operation/ Neglect (M_2)	Maintenance-Induced Faults (M_3)
Engine	20	.10	.15	.05
Fuel	5	.15	.05	.10
Electrical	5	.15	.10	.10
Cooling	5	.10	.15	.10
Transmission/ drive train	15	.10	.15	.10
Brakes/suspension	10	.10	.15	.10

[a]In thousands of miles.

between maintenance actions (T_{actual}) were calculated by the model. Since the data sources provide values for T_{actual} based on the whole vehicle, the model aggregates the subsystem values for T_{actual} to obtain a comparable T_{actual} for the entire vehicle.

The T_o values were estimated in a relative way beginning with the engine. Engines, if manufactured and maintained properly, should require maintenance at approximately 20,000 mile intervals on the average. Maintenance actions as used here refer to anything from replacing an oil pump to a ring or valve job. The T_o values for other subsystems were assigned relative to the T_o value for the engine. For example, the brakes/suspension subsystem would require maintenance approximately twice as often as the engine, because of brake shoe and lining wear. The fuel, electrical, and cooling subsystems, since they contain components that are more frequently maintained (for example, the carburetor, the batteries, and the radiator) were assigned a T_o of 5000 miles. This implies that maintenance actions on these three subsystems are required four times as frequently as on the engine, which seems reasonable. The transmission/drive train (containing the clutch assembly as well as the transmission) was thought to require maintenance somewhat more frequently than the engine, but less frequently than the brakes/suspension. It was therefore assigned a T_o of 15,000 miles.

The magnitudes of the problems listed in Table 6 were derived using the same type of reasoning. Values for the three problems were first assigned for the engine. The problem magnitudes for all other subsystems were then assigned relative to the engine values.

Considering the engine, it was thought that improper operation/ neglect (M_2) should have a higher magnitude than the other two problems, primarily because the oil system, including the oil filter, is a component of the engine and is often neglected. The low value for maintenance-induced faults (M_3) for the engine can be justified by the higher quality of both tools and mechanics required for engine work. This is verified in Table 4, which shows that all engine repair and replacement takes place at the direct support level or above. It also seems reasonable to assume that the magnitude of manufacturing faults (M_1) would be between the magnitudes of the other two problems. For example, an improperly machined oil filter (M_1) is not as likely as neglect of oil level (M_2), but is probably more likely than forgetting to replace the drain plug after draining and adding new oil (M_3).

Since the fuel and electrical subsystems have far more parts than the other subsystems, it was assumed that there was a higher possibility of manufacturing faults (M_1) for these two subsystems. They were therefore given values 50 percent larger (0.15) than the other four subsystems. A value of 0.15 for improper operation/ neglect (M_2) was assigned to the cooling subsystem primarily because of coolant level neglect, which is known to be prevalent. The same value was given to both the transmission/drive train and the brakes/ suspension but, in this case, because of improper operating practices, such as riding the clutch or brakes, overspeeding, etc. In the fuel subsystem, there is less possibility for either neglect or improper operation (fuel contamination is not considered here) and

consequently, it was assigned a low value (0.05). Neglect of the battery is the primary reason for assignment of the 0.10 value to the electrical subsystem. With regard to maintenance-induced faults (M_3), it was assumed that all subsystems other than the engine would have higher values. The other five subsystems are more subject to maintenance-induced faults, since some of their maintenance is performed at the organizational level (Table 4). The values listed in Table 6 were used as inputs to the model.

MADAM, through the calculation process of Table 5, using the input values for T_o and M_i, calculated a value for the mean miles between unscheduled maintenance actions (T_{actual}) of 911 miles for the vehicle as a whole. To ascertain the contributions of the problems to this parameter, another case was considered. T_o for each subsystem was the value specified in Table 6, but all values for the problems (M_1, M_2, M_3) were set equal to zero. The T_{actual} obtained for this case was 1286 miles. The results of the two cases, the "estimated problems" (using the values of Table 6), and the "no problems" (all problem magnitudes set equal to zero) are shown on the left side of Table 7.

The right side of Table 7 provides values for the mean miles between unscheduled maintenance actions (T_{actual}) extracted from the three available data sources. The ARENBD test data, which consider only one vehicle and do not, therefore, contain a reliable sample size, fall between the higher AMSAA result and the lower MMC (worldwide weighted average) result.

Table 7

MEAN MILES BETWEEN UNSCHEDULED MAINTENANCE ACTIONS--RESULTS

MADAM Results	Other Results
911 (Estimated problems) = T_{actual}	AMSAA (TAERS)
1,286 (No problems) = T_o	1,370
	MMC (SDC)
	729 (Worldwide)
	1,122 (Pacific)
	765 (Europe)
	613 (CONUS)
	ARENBD (TEST)
	1,825 ("Failures" only)
	1,115 (All unscheduled maintenance actions)

The comparable T_{actual} obtained from MADAM is 911 (with the estimated problem contributions). The MADAM value falls within range of the data sources and does not seem unreasonable. The difference in the two values obtained from MADAM (1286 versus 911) illustrates the leverage from elimination of the problems. Complete elimination of the problems would increase the mean miles between unscheduled maintenance actions for the vehicle by 375 miles.

Once the frequency of unscheduled maintenance actions was calibrated to the existing data, the amount of resources expended during each of these actions was considered. These resources are composed of two contributions, the mean person-hours and the mean parts cost per unscheduled maintenance action. The action person-hours (L_{actual}) and parts costs (P_{actual}) were calculated using the second and third relationships of Table 5. The ideal person-

hours (L_o) and parts costs (P_o) for a given maintenance action are increased when the appropriate problem impacts are incorporated (M_j and M_k, respectively).

Table 8 lists the mean person-hours for an unscheduled maintenance action (L_o), for each of the six subsystems. Also shown in Table 8 are the estimated contributions of the problems (M_4 through M_8) that cause an increase in the estimated L_o values. These values were used as the model inputs, and were determined using the same estimation technique as was used for the T_o values. They are the number of person-hours required to accomplish an unscheduled maintenance action on the indicated subsystem assuming no problem contributions.

The L_o for the engine was the first value assigned. Any engine work, by necessity, involves access time. Thus, considering

Table 8

MEAN PERSON-HOURS PER UNSCHEDULED MAINTENANCE ACTION--MADAM INPUTS

Subsystem	No Problems (L_o)	Problem Magnitudes (M_j)				
		Inefficient Fault Isolation (M_4)	Faulty Malfunction Diagnosis (M_5)	Late Detection (M_6)	Excessive Rework (M_7)	Low Productivity (M_8)
Engine	4	.40	.10	.30	.10	.10
Fuel	1	.40	.40	.01	.10	.10
Electrical	1	.50	.50	.01	.10	.10
Cooling	1	.10	.10	.01	.10	.10
Transmission/ drive train	3	.15	.05	.20	.10	.10
Brakes/suspension	2	.20	.05	.20	.10	.10

that some of the maintenance actions would be ring or valve jobs and some would be oil pump repairs, the value of four hours for a typical action was assigned. Since the transmission/drive train subsystem also involves access time (although not as much as when repairing the engine), it was given the next highest value of three hours. Although access to the brakes/suspension is not complicated, the subsystem does require maintenance of multiple components (four brakes, four shocks, etc). Thus, it was assigned a value of two hours. The other three subsystems (fuel, electrical, and cooling), although they contain many components, generally involve relatively straightforward maintenance actions. It was thought, therefore, that one hour of labor should be sufficient for each.

The highest value for the engine (0.40) was assigned to inefficient fault isolation (M_4). Inefficient fault isolation is simply a measure of the excess time it takes to identify the fault; mechanics, through lack of adequate training or equipment, often take longer than necessary to diagnose problems. The next highest problem magnitude for the engine was 0.30 for late detection of faults (M_6). This problem is subject to two considerations: how long a fault can remain undetected and how bad the consequences are as a result of its late detection. In the case of the engine, late detection can be disastrous. For example, a malfunctioning oil pump, if left undetected, could cause permanent engine damage, possibly leading to an engine replacement. It was thought that the magnitudes of faulty malfunction diagnosis (M_5) (incorrectly diagnosing the malfunction), excessive rework (M_7) (redoing the maintenance action), and low

productivity (M_8) (taking excessive time to accomplish the repair), were rather small (0.10). All other subsystems were assigned problem magnitudes relative to those of the engine, as before.

The left side of Table 9 lists the values for L_{actual} obtained from the model when the values specified in Table 8 for L_o and M_4 through M_8 are used as inputs. The MADAM results show that with the estimated problem contributions, a typical maintenance action requires 4.1 person-hours. If all problems are eliminated, this can be reduced to 1.4 hours. On the right side of Table 9 are shown the values for L_{actual} obtained from the three data sources.

Table 10 lists the mean parts cost per unscheduled maintenance action (P_o) as well as the problem contributions (M_9 through M_{11}) that were input to the model. There are no values for inefficient

Table 9

MEAN PERSON-HOURS PER UNSCHEDULED MAINTENANCE ACTION--RESULTS

MADAM Results	Other Results
4.1 (Estimated problems) = L_{actual}	AMSAA (TAERS)
1.4 (No problems) = L_o	2.9
	MMC (SDC)
	2.8 (Worldwide)
	2.8 (Pacific)
	2.6 (Europe)
	3.3 (CONUS)
	ARENBD (TEST)
	2.0 ("Failures" only)
	3.4 (All unscheduled maintenance actions)

fault isolation or low productivity, since these have been assumed to have only a labor implication. The engine has the highest mean parts cost per action, since engine components are often expensive. Table 11 shows parts costs taken from the three data sources and the results MADAM gives when the values of Table 10 are used as inputs. Parts costs could not be developed from the ARENBD test data and, therefore, no value could be presented. In the case of MMC, the parts consumption in Europe seems to have driven up the worldwide weighted average to a value that is probably unrealistically high. A value of $54 was obtained from MADAM assuming the problem impacts shown. With elimination of these problems, a parts cost savings of $29 per unscheduled maintenance action could be achieved.

Table 10

MEAN PARTS COST PER UNSCHEDULED MAINTENANCE ACTION--MADAM INPUTS

(In FY 1975 dollars)

Subsystem	No Problems (P_o)	Problem Magnitudes (M_k)				
		Inefficient Fault Isolation	Faulty Malfunction Diagnosis (M_9)	Late Detection (M_{10})	Excessive Rework (M_{11})	Low Productivity
Engine	60	--	.30	.30	.10	--
Fuel	20	--	.50	.01	.10	--
Electrical	30	--	.60	.01	.10	--
Cooling	15	--	.15	.01	.10	--
Transmission/ drive train	40	--	.10	.20	.10	--
Brakes/suspension	25	--	.10	.20	.10	--

Table 11

MEAN PARTS COST PER UNSCHEDULED MAINTENANCE ACTION--RESULTS

(In FY 1975 dollars)

MADAM Results	Other Results
54 (Estimated problems) = P_{actual}	AMSAA (TAERS)
25 (No problems) = P_o	52
	MMC (SDC)
	86 (Worldwide)
	41 (Pacific)
	111 (Europe)
	48 (CONUS)

Scheduled Maintenance

Some of the difficulties associated with estimating present scheduled maintenance costs are described in Sec. IV. The frequency with which scheduled maintenance is performed is currently under review in the Army. A Reduced Maintenance Program has been instituted and further examination of the issue will continue. Thus, it is not presently clear how often scheduled services actually take place. However, there is a standard requirement list for scheduled services which specifies the frequency and the required actions, and, for purposes of the model calibration, it has been adopted. The cost for scheduled maintenance has been considered as a constant in the model and Table 12 illustrates how it was derived. The numbers shown for person-hours and parts cost were estimated as before and are cumulative. That is, during the annual service, both the sixth 1000-mile service and the second semiannual service are also

performed (assuming an annual vehicle mileage of 6000). For example, the annual service requires only one additional person-hour over the semiannual service. Multiplying the annual person-hours by the labor rate ($7.37 per hour) and adding the resulting labor cost to the parts cost gives a total scheduled maintenance cost of $176 per year. This number was treated as a constant over the 1/4 ton truck lifetime in MADAM.

Table 12

SCHEDULED MAINTENANCE--MADAM INPUTS

Interval	Actions	Person-Hours	Parts Cost (FY 1975 dollars)
• 1000 miles	Lube, checks	2	5
• Semiannual	Oil & filter + above	3	15
• Annual	Drain/refill transmission/differential, repack wheel bearings, + above	4	30

Annual Cost (assuming 6000 miles/year) ($):

Labor	111
Parts	65
Total	176

Total Maintenance Costs

Incorporating the assumptions involving both unscheduled and scheduled maintenance into MADAM, the total annual maintenance costs for the 1/4 ton truck with and without problem contributions were calculated. These results are shown in Table 13 along with total costs obtained from the three sources of data (adjusted to 6000 miles per year). The numbers in brackets give the annual maintenance cost per mile for the vehicle, again assuming 6000 miles per year. The

Table 13

OVERALL ANNUAL MAINTENANCE COSTS--RESULTS

(In FY 1975 dollars, assuming 6000 miles per year)

MADAM Results	Other Results
727 (Estimated problems)(12.1¢/mile)	AMSAA (TAERS)
343 (No problems)(5.7¢/mile)	456 (7.6¢/mile)
	MMC (SDC)
	990 (Worldwide)(16.5¢/mile)
	468 (Pacific)(7.8¢/mile)
	1,122 (Europe)(18.7¢/mile)
	816 (CONUS)(13.6¢/mile)

MMC worldwide value is more than twice the AMSAA value, illustrating the large variations by source. MADAM calculates a cost per mile of 12.1 cents, including the estimated problems, which is within the range of the MMC and AMSAA values. When the problems are eliminated (set equal to zero), MADAM obtains 5.7 cents per mile.

Thus, using the estimated problem magnitudes, the potential maximum savings would be \$384 (\$727 versus \$343) per vehicle annually. The cost breakdown is as follows:

	Parts	Labor	Total
Base Case	\$418	\$308	\$727
No Problems	184	160	343
Max. Savings	\$234	\$148	\$384

Because of the need for sufficient mechanics to meet wartime needs and peacetime peak demands, the labor savings achievable are likely

to be less than the calculated \$148 per vehicle per year. One estimate, based on Rand-Air Force experience, is that achievable labor savings may be 70 to 85 percent of those calculated, or from \$104 to \$126 per vehicle per year. There are approximately 45,000 1/4 ton trucks in active use [3], so the potential savings for this class of vehicle could be as high as \$15 million - \$17 million annually.

All of the values obtained through the calibration procedure are of course only estimates. The three data sources from which the standard values for calibration were extracted are themselves somewhat inconsistent and unreliable. Until current maintenance costs are known with much more certainty, any analyses will necessarily involve considerable dependence on judgment.

Availability

Table 14 shows inherent availability values obtained from the three data sources and MADAM. This availability measure can be

Table 14

OVERALL AVAILABILITY--RESULTS

MADAM Results	Other Results
0.93 (Estimated problems)	AMSAA (TAERS)
0.96 (No problems)	0.95
	MMC (SDC)
	0.94 (Worldwide)
	0.94 (Pacific)
	0.94 (Europe)
	0.92 (CONUS)
	ARENBD (TEST)
	0.98 ("Failures" only)
	0.96 (All maintenance)

misleading as a true determination of fleet availability, since the calculational procedure does not account for time spent waiting for parts or for maintenance. However, it does provide an additional measure of the potential impact of diagnostic aid systems.

SAMPLE MADAM APPLICATIONS

MADAM offers a tool for several possible areas of investigation in the field of land vehicle maintenance costs. At this point in the study, two areas of sensitivity have been addressed.

The first area was to identify those problems that would provide the most leverage in reducing maintenance costs, if they could be eliminated. The approach developed to answer this question is as follows: Successive model results were obtained with each of the problems independently assigned a magnitude of zero, while the magnitudes of all other problems were held constant at the values specified in the calibration procedure. The results provided the basis for a ranking of the problems' capability to reduce total maintenance cost through their elimination. MADAM was then run several times, each time successively removing the problem that would have the most leverage in reducing maintenance costs. A bar chart illustrating the results of this process is shown in Fig. 5. With all the contributing problems present (the base case), the total maintenance cost per vehicle is \$727 annually, while with all problems eliminated this cost is reduced by 53 percent, to \$343. The elimination of faulty malfunction diagnosis alone provides a 27 percent decrease from the base case. More than half the savings in

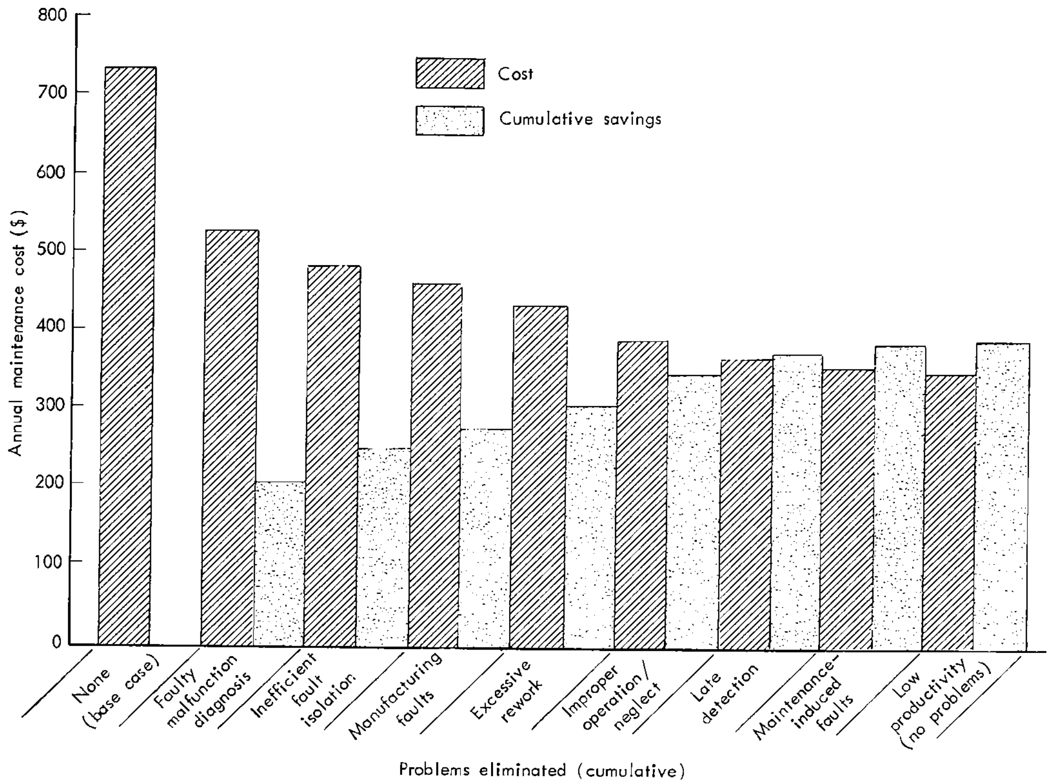

Fig. 5—Annual maintenance costs and savings as problems are eliminated

going from the base case to the "no problems" case (34 percent out of a possible 53 percent) can be achieved by eliminating only two of the problems--faulty malfunction diagnosis and inefficient fault isolation. A sensitivity analysis of this type can provide useful guidance as to which function(s) a proposed diagnostic aid system should perform for maximum benefit. It could also provide the basis for comparison of two proposed systems capable of performing different diagnostic functions.

A second sensitivity analysis was examination of the estimated problem magnitudes. If they were higher than originally estimated, maintenance costs would be driven up. A given problem magnitude, however, could not simply be arbitrarily increased, since there would be no basis for doing so. In addition, the quality of the available data is such that examination of numerous cases is not justified. Since it was felt that the relative magnitudes of the problems were essentially correct, all problem magnitudes were increased proportionately.

The results of this analysis are shown in Fig. 6. The first and second points are the "no problems" case and the base case

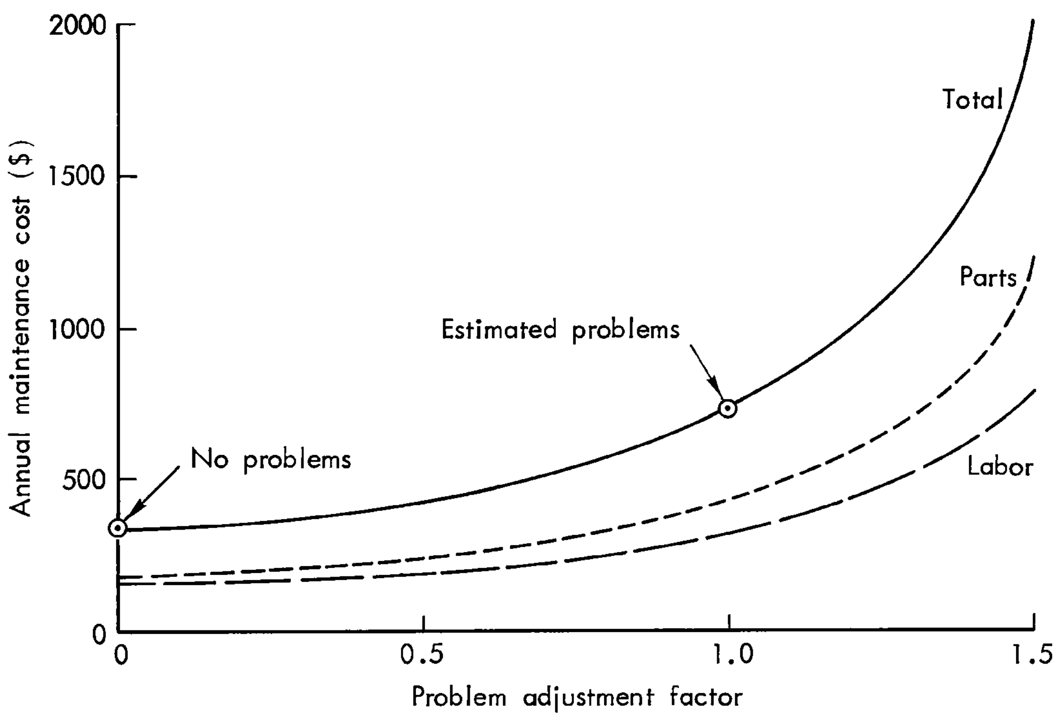

Fig. 6 — Annual maintenance costs as problem magnitudes are increased

("estimated problems"), respectively. Although the annual total cost per vehicle increases fairly slowly up to approximately the base case level, after this point there is almost an exponentially increasing dependence. A sensitivity analysis of this type is useful in that it provides more insight into the effect of the problem contributions on the annual costs of maintenance. It indicates that although the problem magnitudes assigned in this study may not be exact, they are probably within reasonable range of the correct values.

In addition to sensitivity studies of the problem magnitudes, it was thought desirable to examine the impacts of performing selected diagnostic functions. An excursion based on use of the STE/ICE [3] system was performed on the base case obtained from MADAM. As in the STE/ICE study, diagnostic impacts were restricted to three vehicle subsystems (engine, fuel, and electrical). The improvements were assumed to apply to faulty malfunction diagnosis (parts and labor), inefficient fault isolation (labor), and late detection of faults (parts and labor). Values for the improvement factors are as follows:

	Parts	Labor
Faulty malfunction diagnosis	.27	.27
Inefficient fault isolation	--	.29
Late detection	.09	.09

If, for example, the fuel system labor improvement is considered, the relevant equation is Eq. (6), where

$$L_{actual} = L_o / \prod_j [1 - M_j(1 - D_j)] \tag{6}$$

If the improvements in the three problems given above are substituted into the equation along with the other appropriate values, the following relationship is obtained:

$$L_{actual} = 1/[1 - .4(1 - .29)][1 - .4(1 - .27)][1 - .01(1 - .09)][1 - .1][1 - .1]$$
$$= 2.46$$

The comparable value for the base case (assuming no diagnosis) was 3.46 hours. Thus, the diagnosis provides a savings of one person-hour of labor in each unscheduled maintenance action on the fuel system.

If the diagnostic improvement factors shown above for all three subsystems are input to MADAM, a value of $623 for the annual total cost is obtained. This represents a savings of $104 (14 percent) over the base case value of $727. If the late detection improvement factor is not considered (as was the case in the STE/ICE study), then only two improvement factors, those for inefficient fault isolation and faulty malfunction diagnosis, remain. In this case, the model obtained a total annual cost savings of $102 over the base case.

A further exercise of interest was a comparison of the results generated by the calibration of MADAM to those of a study by the U.S. Army Ordnance Center and School [11], which used a somewhat similar approach. The purpose of the latter study was to determine the parts and labor necessary to perform nondeferrable maintenance on 100 vehicles for 120 days in a European wartime scenario. Although our study is concerned with vehicles that experience much less intensive peacetime use (6000 miles/year as opposed to approximately 6000 miles/120 days), it was thought that a comparison would be

interesting and would provide an independent check on the reasonableness of MADAM results.

The parts and labor requirements for the Ordnance School study were estimated by a group of maintenance NCOs with a combined experience of about 200 years. The raw Ordnance School data were reduced to a form that could be compared to the MADAM results. Table 15 illustrates this comparison.

Table 15

MAINTENANCE COSTS PER VEHICLE
(Cost per mile in parentheses)

Source	Mileage	Labor Rate	Labor Cost	Parts Cost	Total Cost
Ordnance school	6000/120 days	\$7.37	\$320 (5.3¢)	\$462 (7.7¢)	\$782 (13.0¢)
MADAM	6000/year	\$7.37	\$309 (5.1¢)	\$418 (7.0¢)	\$727 (12.1¢)

INCOMPLETE AREAS

The most obvious advantage of MADAM is its capability to examine and quantify, albeit parametrically, the impact of diagnostic aid systems on Army land vehicle maintenance costs. However, like any model designed for a specific purpose, it also has several limitations, all of which are related to the lack of good maintenance data. If, for example, the problems or the diagnostic functions (or both) have not been correctly or completely specified, results from the model cannot be interpreted in an absolute way. It is for this reason that we stress only the parametric value of a methodology of this type.

Due to the quality of the available data, the calibration of MADAM was not straightforward. In addition, since field data provide information on maintenance actions based only on vehicle mileage, the model does not account for important variables such as vehicle operating hours or calendar age. Consider, for example, two vehicles--one spends a large amount of its operating time idling, the other travels only on good roads. The maintenance requirements for the subsystems of the two vehicles are bound to differ. Calendar age could prove an important variable, since an older vehicle may experience more frequent subsystem failures than a younger vehicle, under similar operating conditions. MADAM is capable of determining maintenance costs on the basis of vehicle age. However, since few data are available relating age to maintenance requirements, no calibration can be performed.

The field-test (ARENBD) data, unlike the field-operating (TAERS, SDC) data, do account for both age and operating hours. Direct translation of test conditions to field operations, however, is very difficult. Indications are that vehicle experiences in the operating environment are different from test conditions. Two variables account for this difference: the use profile of the vehicle in operating units (good roads, bad roads, excessive idling), and the problems inherent within the maintenance system. However, data that examine use profiles are not presently available.

The model presently examines faults only for subsystems. This is perhaps an oversimplification. Certain components may be almost entirely responsible for a high incidence of malfunction within a subsystem, but there are no data to confirm this.

A better measure of availability is clearly needed. More reliable data on maintenance actions and vehicle use could provide the means to do this. Presently, availability is determined on the basis of mileage, whereas a more useful measure might be obtained through actual clock hours and estimates of time spent waiting for maintenance or parts.

The model, if wisely used for parameterization as opposed to absolute determination, can be a valuable instrument for evaluation of policy alternatives in the use of diagnostic aid systems, and also for focusing judgments and intuitions regarding current vehicle maintenance. The approach adopted here sheds light on both the utility of diagnostic aids and the estimation of maintenance costs.

IV. DATA REQUIREMENTS

In Secs. V and VI, the sources of land vehicle maintenance data and the difficulties associated with extracting meaningful costs will be discussed in general and with respect to the 1/4 ton truck. This section examines the data required for analysis of the potential savings in maintenance costs resulting from the use of diagnostic aid systems.

Our approach to estimating maintenance cost savings requires a knowledge of current Army field and maintenance operations, practices, and costs. Given estimates of current maintenance costs, the operating and maintenance "problems"* that presently exist, and their magnitudes, it is possible to estimate the potential leverage of diagnostic aid systems. Potential leverage is the difference between current maintenance costs (which include contributions by existing problems) and maintenance costs if all problems could be eliminated. Obviously, diagnostic aid systems cannot eliminate all the problems; estimates of their actual impacts are therefore necessary. These estimates are in terms of the extent to which the various problems could be ameliorated. This approach was implemented in MADAM, which is described generally in Table 16.

To define a base case, MADAM was calibrated using estimated current maintenance costs for the 1/4 ton truck. The inputs required

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*A "problem" is defined as anything that contributes to higher-than-necessary maintenance costs. Specific "problems" were defined in Sec. II.

Table 16

MADAM DESCRIPTION

Given:

- Miles of operation
- Frequency of maintenance actions
- Resources required per maintenance action
- Problem magnitudes and areas of impact
- Diagnostic areas of impact and effectiveness

Calculate consequences:

- With and without diagnostics

to do this were of three types: the frequency of maintenance actions, the labor hours, and the parts cost incurred by each action. The specific types of data required are described below.*

SCHEDULED MAINTENANCE

For a complete analysis of the impacts of diagnostic aids on Army maintenance costs, the implications of scheduled maintenance should be considered. Vehicle operators' manuals prescribe scheduled maintenance intervals and the actions to be performed [12]. There are basically three types of scheduled maintenance: 1000 mile service, 6000 mile (semiannual) service, and 12,000 mile (annual) service.** Table 17 lists the actions to be accomplished by the mechanic for each type of scheduled maintenance on the 1/4 ton truck.

*Although maintenance costs for other vehicles would be estimated in a similar fashion, the following discussion pertains specifically to the 1/4 ton truck.

**The 6000 and 12,000 mile services are performed on a time-or-miles (whichever occurs first) basis.

Table 17

1/4 TON TRUCK SCHEDULED MAINTENANCE ACTIONS

- 1000 miles

  Lube:

  - Front and rear axle drive U-joints
  - Suspension ball joints
  - Front and rear propeller shaft U-joints
  - Steering linkage
  - Pintle
  - All hinges, latches, etc.

  Check and fill (if needed):

  - Front and rear differentials
  - Brake master cylinder
  - Transmission

  Other

  - Clean and refill air cleaner oil reservoir

- 6000 miles/6 months

  - Drain and refill crankcase
  - Change engine oil filter
  - Lube distributor

- 12,000 miles/12 months

  - Drain and refill front and rear differentials
  - Repack front and rear wheel bearings
  - Drain and refill transmission
  - Drain and refill transfer

SOURCE: Ref. 12.

Although the standards are extremely specific with regard to the mileage/time intervals, there is evidence that scheduled maintenance is not done accordingly.* Some of the 1000 mile services are probably skipped completely; however, since they are more important

*Data from the 1/4 ton truck SDC [10] imply that scheduled maintenance is performed about half as often as the standards require. Part of this difference may of course be due to incomplete reporting.

and less frequent, the annual and semiannual services may be more likely to be done according to the prescribed time intervals. In addition, the Army is presently questioning the efficacy of current standards for scheduled maintenance.* There are indications that, for more efficient utilization of resources, schedules should provide for less frequent maintenance actions (for example, wheel bearings may not need repacking every 12,000 miles or 12 months; excessive maintenance may even be harmful). Thus the standard requirements may change at any moment and, in any case, adherence to them presently appears sporadic at best. There are few data available to indicate what resources are actually expended in scheduled maintenance. For purposes of this study then, we assumed that the requirements dictated by the standard are followed. Although scheduled maintenance was treated as a constant throughput in MADAM, the provision for alternative treatment does exist, should additional data become available.

UNSCHEDULED MAINTENANCE

The data requirements for unscheduled maintenance actions are similar to those for scheduled maintenance. That is, the frequency with which maintenance actions are performed and the parts and labor resources associated with each of these actions are the necessary inputs. Unscheduled maintenance is performed only when one of the

*Tests were run under FORSCOM control at Ft. Carson, Colorado, and Ft. Riley, Kansas.

vehicle subsystems appears to require corrective action.* Any maintenance action other than those in Table 17 is assumed to be an unscheduled action. Field data providing the mean time between unscheduled maintenance actions (either by mileage or calendar time) for each of the vehicle subsystems, as well as the parts and labor expended in each action, would be extremely valuable. Such data are available to some extent. In addition to test data [8], which may not be particularly applicable to field conditions, TAERS and SDC data can be used. Other vehicle maintenance studies can also provide inputs. However, as will be discussed in Sec. VI, inconsistencies exist within data sources and from source to source. Therefore, no single data source can provide complete and consistent values for model calibration purposes. Further, to utilize the available data, numerous assumptions and judgments are required.

GENERAL INFORMATION

If frequency of maintenance actions and the associated resources expended can be estimated at least parametrically, then estimates of total maintenance cost may be derived in the following way. The direct labor rate (cost per person-hour of actual direct productive maintenance, often called "wrench-turning" time) plus the overhead labor rate (costs for indirect productive time, nonproductive time, and supervisory time) is multiplied by the total number of direct

*The word "failure" will not be used here. To classify an unscheduled maintenance action as a true "failure," a list of specific conditions must be satisfied.

person-hours expended on all maintenance actions. This labor cost is then added to the cost of parts consumed during maintenance.

Parts costs have proven difficult to obtain. The Army Master Data File (AMDF) [13] contains a list of Army parts and their associated costs by Federal/National Stock Number (FSN/NSN), but it would present an almost insurmountable task to manually extract 1/4 ton truck parts costs from this extensive list.* Further, some of the data (the ARENBD test data, in particular) list some parts by part number instead of by FSN. Since the AMDF does not contain part numbers, it is difficult if not impossible to determine the cost of these parts.** Another disadvantage of the AMDF is that it probably contains costs for parts purchased several years ago. We have attempted to use, in addition to the AMDF, "purified" TAERS and SDC parts lists*** to determine parts costs for the 1/4 ton truck.

DATA ON MAINTENANCE PROBLEMS

As mentioned previously, we have defined a set of problems that increase the costs of unscheduled maintenance actions. If data describing the prevalence and magnitudes of these problems could be obtained, we could then determine a minimum cost for performing maintenance (i.e., the cost if no "problems" existed). However, to

*The AMDF is stored on magnetic tape; a microfiche version contains over 17,000 pages of computer output and about one million items.

**Even using part numbers, part names, and the parts manuals, some FSNs could not be identified.

***Supplied by Ray Bell of AMSAA.

our knowledge, little data related to these maintenance problems exist.* Consequently, we have been forced to estimate the magnitudes of the problems to obtain a minimum cost case.

VEHICLE USE PROFILE

An average vehicle of a certain type may not adequately represent all vehicles of that type. It is preferable to classify vehicles of a particular type according to how they are used. For example, some vehicles may generally travel at high speeds with light loads over good terrain, whereas others travel rough terrain with heavy loads. The portion of time (in hours) or distance (in miles) that a vehicle spends in these states and the resulting maintenance pattern could provide the basis for establishing a vehicle use profile. Unfortunately, data of this sort are also unavailable.**

*Limited data are available on some maintenance problems. A 1966 study found that 30 to 50 percent of automotive malfunctions were improperly diagnosed [14]. Data on improper diagnosis, secondary faults (malfunctions caused by other malfunctions), and excessive test times are given in Ref. 3.

**Development of this type of data was proposed by Alvarez and Randall [15] and Emanuel [16].

V. AN OVERVIEW OF DATA SOURCES

Since the early 1960s, the Army has expended considerable effort to obtain accurate data on the maintenance and status of its vehicles. Several data collection systems were implemented, and met with varying degrees of success. In this section we discuss these Army efforts, their results, and the implications for our study (or for any study that requires estimates of the resources expended on vehicle maintenance). Actual numerical data for the 1/4 ton truck are shown in Sec. VI.

ARMY LAND VEHICLE MAINTENANCE DATA SYSTEMS

The most extensive data system by far was the Army Equipment Records System (TAERS), introduced in 1962 and discontinued in 1969. TAERS was an attempt at exhaustive reporting--every maintenance action was to be entered into a massive computerized data base at the Logistics Data Center (later the Maintenance Management Center (MMC); now the Materiel Readiness Support Activity (MRSA)), located at the Lexington Bluegrass Army Depot, Kentucky. Maintenance actions at the organizational level were recorded on DA Form 2408-3 and those at support levels on DA Form 2407.* Verification of these inputs was limited or completely lacking, and their inaccuracy later became apparent. Not only were the reports often completed by relatively inexperienced and untrained people who tended to be

*This discussion of TAERS applies only to non-aircraft maintenance. Slightly different procedures were followed for aircraft.

careless, but commanders began using the reports to measure job performance, creating incentives for deliberate falsification. In an evaluation late in 1968, the Army decided that TAERS was not cost effective. Three primary reasons for this conclusion were: (1) The amount of data was too voluminous for timely processing and its utilization was questionable; (2) collection and processing costs were prohibitive; (3) the validity of the data was suspect, because of the conditions under which they were collected. As a result, TAERS was reduced in scope, otherwise modified, and became the Army Maintenance Management System (TAMMS) [14].

Despite the demise of TAERS, data collected during its existence are still available. For example, a TAERS data base exists for the 1/4 ton truck and covers the years 1965 to 1969. Use of TAERS data, however, requires a very large additional data processing effort (to deal with incomplete reporting, erroneous mileage/date sequences, inconsistent part names/stock numbers, and so on). Only two groups have used TAERS extensively--the Army Materiel Systems Analysis Activity (AMSAA) in its useful life studies of 1/4 ton, 2-1/2 ton, and 5 ton trucks [9,17,18], and Teledyne-Continental Motors in studies related to tank engines and tank recovery vehicles [6,7]. As an indication of the effort required to use TAERS data, AMSAA estimates that a useful life analysis requires $50,000 to $75,000 of computer time and about two person-years of effort, given that the basic computer programs have already been developed.*

*Personal communication from Ray Bell of AMSAA, 1976. Processing of TAERS data required the use of 27 major computer programs, three programming languages, and ten reels of tape to order and analyze each reel of TAERS data [17].

TAMMS (the successor to TAERS) also has flaws. Although data are no longer transmitted to MMC* and the reporting requirements have been reduced in comparison to TAERS, the system is still complex and imposes an onerous paperwork burden at the unit level [19]. TAMMS data also suffer from the same lack of verification that plagued TAERS.

A new system called SAMS (Standard Army Maintenance System) is now evolving. SAMS is intended to standardize and simplify maintenance management, procedures, operations, information systems, reporting requirements, and data flows on an Army-wide basis. SAMS is one segment of the Standard Army Logistics System (SALS), and is expected to begin providing useful data in 1982.**

When TAERS was simplified to TAMMS, detailed maintenance data were no longer sent to national levels (MMC and Department of the Army). However, the Army still required such field data from the unit level for product improvement and other purposes. To fill this need, the Sample Data Collection (SDC) program was developed and published in AR 750-37 [20]. SDC allows data to be collected on a selected sample*** of a specific vehicle type over a limited period (two years is a typical length for an SDC plan). Data are collected

*Except for data on Modification Work Orders, SDC items, Equipment Improvement Reports, and materiel readiness.

**The proponent for SAMS is the office of the Deputy Chief of Staff for Logistics, Department of the Army.

***Sample size is chosen to achieve 90 to 95 percent confidence in the results.

through Form 2407s by the TAMMS clerk, with the assistance and supervision of field maintenance technicians* assigned to the post; control and data processing are by MMC. SDC objectives are to conserve resources at all levels, reduce the volume of data to a manageable level, improve the quality and accuracy of the data, and reduce interference with field units [14].

The cost of a particular SDC plan can vary greatly, depending on the number of sites, units, and vehicles, and the degree of control; in a "fully controlled" or "intense" SDC, special data collection teams are deployed to the field, keep the equipment under nearly constant observation, and report all maintenance actions. Because of the obvious expense, very few SDCs are of this type. Another factor that influences SDC quality is command and field maintenance technician interest; if the unit commander is indifferent to the SDC, data reporting is likely to be incomplete or inaccurate. Likewise, if the field maintenance technician sees his role as merely picking up forms once a month and shipping them to MMC, the quality of the data will suffer.

Processing of SDC data can also cause difficulties. In the 1/4 ton truck SDC report [10], we discovered an inconsistency between two sets of numbers, believed to be the result of a programming error. Several phone calls to TACOM and MMC were necessary before we were able to reach this conclusion, partly because of divided responsibility (TACOM ordered the SDC and specified what calculations

*Field maintenance technicians are primarily under the control of TACOM; their principal duty is to report vehicle deficiencies in the field and suggestions for improvement. Their time is, in many instances, controlled by the units to which they are assigned.

were to be made, whereas MMC controlled the SDC and processed the data). This division of responsibility, in conjunction with a two-year lapse since the report was produced, resulted in confusion as to just what each set of numbers was supposed to represent. In fairness to the SDC concept, however, we should point out that the 1/4 ton truck report was one of the first completed* and some procedures and details may have been affected by shakedown problems, which may have since been resolved.

In addition to the major Army-wide efforts discussed above, other attempts to gather data have been and are being made at some post and unit levels. The effort by the U.S. Army Armor Center and Ft. Knox Comptroller [21] is one of these--operating costs for 167 vehicles in two brigades were collected for six months, and processed by manual methods, to determine the cost per mile to operate and maintain four types of tracked vehicles. Results from such a study are of limited applicability elsewhere, however, and other uses of the data are inhibited because the data do not exist in computerized form. Another effort is under way at Ft. Carson, Colorado, under Forces Command (FORSCOM) auspices--a locally developed financial accounting system is being used to derive parts consumption factors for vehicles, with usable results expected in a year or two. However, no attempt is being made to capture labor costs in that study.

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*Other reports that are either under way or completed relate to the M114A1E1 armored carrier, the M551 Sheridan, the M809 5 ton truck, the M561 1-1/4 ton truck, and new versus overhauled 2-1/2 and 5 ton trucks.

Over the years there have been several major studies of Army vehicles using data from many sources. One of the principal recommendations that emerged from such studies was that the Army develop a vehicle management information system to establish a consistent data base and eliminate the need for repetitive data collection efforts. This recommendation has met considerable resistance because of the anticipated high cost (and probably also because of memories of TAERS). Nevertheless, some attempts are being made to deal with the vehicle data problem.

The most ambitious of these attempts is of course SAMS, discussed above. Others include Logistics Support Analysis (LSA) and the Vehicle Technical Management Information System (VETMIS). LSA applies to new vehicles in the preproduction phase and involves estimates of maintenance and logistics requirements by the vehicle manufacturer [22]. VETMIS applies to vehicles in the field and is an attempt by TACOM to integrate various data sources (Equipment Improvement Reports, Equipment Peformance Reports, etc.) into a more coherent system so that all available data on a given vehicle type can be made accessible to vehicle engineers, designers, and other interested parties [23].

Based on its past experiences with data systems, the Army (which is by no means unique in this regard) appears to have placed too much emphasis on data processing and not enough emphasis on the less glamorous areas of data requirements, collection, and quality. The result has been a considerable ability to store and process large quantities of questionable information.

REPORTS AND STUDIES

In addition to the output of the various data systems, secondary data sources also exist; among these are studies using field data, Army vehicle test reports,* and theoretical estimates of vehicle maintenance costs (without the use of either field or test data).

Among the studies using field data are the AMSAA, Teledyne-Continental, and Armor Center/Ft. Knox Comptroller efforts mentioned above. A precursor to the AMSAA useful life studies was a series on vehicle maintenance and lifetimes done by Research Analysis Corporation [24,25].** Some currently available vehicle data are summarized very briefly in a TACOM quarterly report [26].

Another data source is the vehicle tests conducted by the Armor and Engineer Board (ARENBD) at Ft. Knox, Kentucky, and by the Test and Evaluation Command at Aberdeen Proving Ground, Maryland, and Yuma Proving Ground, Arizona. Such tests are usually performed to insure that vehicle specifications are met; they involve intense use and high mileage over a relatively short period of time (e.g., 20,000 miles on one vehicle in six months or less) [8]. These tests are carefully controlled and test records are probably the most complete and accurate of all data sources, but it is difficult to relate test results to actual field conditions--vehicle use is more intense, supervision is much closer, and both drivers and mechanics are

*Tests by vehicle manufacturers were not considered.

**Research Analysis Corporation has since become the Operations Analysis Division of General Research Corporation (GRC). RAC researchers themselves gathered the data for some of these studies; others were based on TAERS data.

probably better (or at least more careful) than those in operating units. The user of test data must also be aware of how the particular test defines the term "failure;" not all breakdowns or unscheduled maintenance actions are considered failures, and so the actual consumption of maintenance resources is almost always greater than the resources required just to repair "failures." As an example, one test specification* defines a "failure" as a malfunction that cannot be deferred until (1) the next scheduled maintenance (if organizational maintenance is prescribed for correction), or (2) the remainder of the vehicle's life** (if direct or general support maintenance is prescribed for correction). The spec further defines a malfunction as not deferrable if it renders the vehicle inoperable, degrades performance below that required for mission accomplishment, or causes a critical hazard to personnel or equipment. Also, any malfunction that is authorized to be repaired by the operator/crew and can be repaired within 60 minutes using only the tools and spare parts carried with the vehicle will not be considered a failure. In spite of these restrictions, however, test data can provide useful information if interpreted carefully.

A third source derives maintenance costs on a theoretical basis, without using actual vehicle data. Two examples of this type are a TACOM report [27], which estimated (from Army programming and budgeting documents) the entire annual cost of supporting the vehicle

*MIL-T-45331F, specifications for 1/4 ton trucks.

**Before overhaul, rebuild, replacement, or salvage (as applicable).

fleet, and then allocated these overall costs to each individual vehicle type,* and the RCA/TACOM STE/ICE cost-effectiveness study [3], which used these vehicle maintenance costs to estimate the annual savings achievable by deploying a particular diagnostic aid system.

OTHER SOURCES

At this point, given the variety of data sources already discussed, the reader may wonder how the Army determines the number of mechanics to authorize in support of a unit's vehicle complement. The answer is contained in the procedures known as MACRIT (Manpower Authorization Criteria), which are used to develop unit TO&E (Table of Organization and Equipment) personnel spaces. TACOM, as the commodity command responsible for land vehicles, estimates the number of "wrench turning" person-hours required per vehicle per year. The Training and Doctrine Command (TRADOC) then incorporates estimates of indirect, nonproductive, and total available hours per mechanic, and of vehicle density (population) in a given type of unit to determine the number of mechanic spaces that should be authorized. The procedures are specified in AR 570-2 and AMC Supplement 1 to AR 570-2 [28,29]. Unfortunately, there may be inadequate justification for TACOM's original estimates of direct productive maintenance person-hours per vehicle per year, numbers that imply annual labor requirements per vehicle much higher than those obtained from field

*As shown in Sec. VI, this approach yields annual maintenance costs higher than those obtained by other methods.

or test data.* However, since the TACOM person-hour estimates translate directly into personnel spaces, there will likely be resistance to making any significant changes to them; a recent study has recommended several changes in the MACRIT process and calculation procedures [15].

A final word on data sources--many people, when first confronted with the question of how to estimate Army vehicle maintenance costs, suggest using commercial experience (from trucking, taxi, or car rental firms, etc.) as an analog. This is not possible directly, and such estimates might be inaccurate even with a great deal of work. A preliminary investigation along these lines [30] found that

> The problem of making a valid comparison of the two fleets is more complex than it would appear to the casual observer. There are many areas of similarity but there are also many significant differences in procurement philosophy, management goals and operating procedures all of which directly affect fleet operating costs. More significantly, these differences also affect record keeping procedures and lead to problems in securing comparable cost data....The major difference between the two fleets lies in their objectives. The Army objective is to procure and maintain a fleet of vehicles capable of worldwide deployment and with multi-mission potential. The prime requirements for this fleet are reliability, versatility, and availability. These attributes are maximized at the expense of such things as cost, size, complexity, and maintainability. The commercial objective is to procure and maintain a fleet which will haul the required cargo (under carefully defined conditions) for the minimum cost. Their prime requirement is to achieve the lowest operating cost per mile or per revenue dollar. Their goal is to maximize profit by juggling procurement cost, vehicle specifications, maintenance practices, replacement

*MACRIT estimates should be somewhat higher than field or test results, since MACRIT allows for component bench repair and for wartime conditions during a long-term mid-intensity conflict. One of the stated benefits of SDC is to validate maintenance data so that the TO&E can be updated through the MACRIT process [14]. When fielded, SAMS will also provide data for updating the MACRIT.

> intervals and all the other factors involved in the cost-versus-profit analysis. The Army is constrained by a strangling mass of regulations concerning universal capability, world-wide deployment, parts interchangeability, adequate production bases, procurement procedures, and maintainability by [mechanics without adequate academic backgrounds]--official policies which severely limit the options open to military vehicle designers. The commercial operator, while limited to some extent by rulings from labor unions, ICC and other federal and state agencies which specify such things as maximum size and weight, safety features and so forth, is relatively free to select the vehicle he has decided will do his job. He lets the component manufacturer pay for R&D of new items and buys them only after he has assured himself of their suitability for his job either by observations of other fleets or by his own tests of small numbers of the new item in his own fleet.
>
> It is evident that direct comparison of Army fleets with commercial fleets is not possible unless some attempts are made to compensate for the differences listed above.

Following this initial examination, the study formulated some hypotheses dealing with Army versus commercial comparisons and proposed a methodology to test them involving collection of data in a common format, and use of "equivalency factors" to account for different use patterns [16]. Unfortunately, no further work was done and the hypotheses were never tested.

In this section we have tried to acquaint the reader with some of the sources of Army vehicle maintenance data. The information was obtained from reports, interviews, and our own analyses and impressions, and we believe we have presented a fair general picture of current sources of vehicle maintenance data. It is a dynamic subject, on which institutional knowledge is fragmented among many agencies, and regarding which many personal biases (spoken and unspoken) exist.

VI. DATA PROBLEMS

In this section we will consider some of the problems associated with Army vehicle maintenance data, first in general terms and then specifically as illustrated by estimates of maintenance costs for the 1/4 ton truck.

In Sec. V, we described the extensive data processing efforts required to work with TAERS data, and the care required when using test data, with their differences from field conditions, and very specific definitions of "failures." A long-standing, pervasive, and more fundamental problem is the fragmentation of the Army's data sources. A 1967 report [31] put it this way:

> During the MBT-70 analysis, it was necessary to make a number of calls and visits to various commands having needed data. At each command, it was necessary to contact a number of persons individually in search of particular data. Little if any central knowledge or control of data resources was evident.

In the ten years since this was written, the situation has not changed to any great extent. It would be unfair, however, to assume that data problems are unique to the Army; such problems exist in all organizations. Information may be in an inconvenient or unusable format, because the collection and processing systems were designed for other purposes; irregularities, inconsistencies, and gaps in information may exist because of sloppy reporting or changes in procedures over time; and the sample may be too limited in size or scope to permit much confidence in the results [32]. In addition to

general data problems, however, some difficulties are caused or aggravated by institutional aspects unique to the Army.

PHILOSOPHY AND OBJECTIVES

One institutional aspect unique to the Army is its organizational philosophy (compared to that of the Air Force). Whereas Air Force units are organized around a single aircraft type (A-7 squadrons, F-4 squadrons, etc.), Army units have mixes of many types of equipment. A tank battalion, for example, contains 54 tanks, 28 armored carriers (4 different types*), 96 trucks (5 types), and 12 other vehicles (4 types), for a total of 190 vehicles (excluding trailers). The difference in organization is often summed up by the phrase "The Army equips its men, while the Air Force mans its equipment." The single-equipment-type orientation tends to simplify the cost-estimation process somewhat,** whereas the "mix" orientation tends to complicate it.

An even more fundamental problem (again not unique to the Army) derives from the nature of bureaucracies; while analysts can do little about this, they must be aware of it. As Stockfisch put it [34],

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*Several different models may be present within a given vehicle type. For some examples, see Ref. 12.

**The process involved is still far from straightforward. Difficulties occur with multiple data systems, different data nomenclatures, and insufficient data quality and quantity [33].

> ...bureau heads tend to be secretive and obfuscate about their production processes....Subordinates may conceal information about their capability so that either they can receive less demanding assignments, or achieve given assignments and quotas with less effort, or exceed assignments should occasions arise that afford exceptional reward for doing so....Because [information] must flow upward through the hierarchy, it is often edited or aggregated....Given the need to aggregate, there is opportunity to adjust or modify the material....Intertwined with some valid data and large amounts of pseudodata are substantial information gaps, or voids. This condition exists in part because organizations and groups are often unwilling to undertake a quest for information that offers some prospect of revealing adverse findings....Manipulation of data, including avoidance of collecting important kinds of data, becomes a feature of a bureau's "management." One consequence of this behavior is that a bureau head may not be able to manage his organization even if he "wanted" to.

Collecting data, especially meaningful or detailed data, can also be (and usually is) an expensive process. Funds for data collection may have to be obtained by cutting other programs; in the experience of TACOM staff members, for example, it has often been difficult to justify spending even $60,000 on data collection when the same amount would pay for a tank overhaul.*

In many instances when the Army does collect data, the objectives are to develop factors rather than to estimate or analyze costs. Two examples of this are the Ft. Knox and Ft. Carson efforts mentioned in Sec. V. In the Ft. Knox study, factors were developed for "projecting budget requirements and for use in decrementing exercises...." [21]; the objective of the Ft. Carson effort is similar, but restricted to parts costs.** Judging by the information

*Personal communication from Dave Shehane of TACOM, 1976.

**Personal communication from Dan Simpson of FORSCOM, 1976.

we have obtained from sources throughout the Army (Department of the Army, Materiel Command, Forces Command, Tank-Automotive Command, and individual Army posts), from the results of a study of the MACRIT process [15], and from other studies, the Army knows very little about the resources required to maintain and operate its vehicles, especially in a micro sense. This raised Congressional interest in the past [16,30] and will probably continue to do so in the future. Attempts to produce rudimentary cost factors are a first step which, if successful, could lay the groundwork for more detailed analysis of what vehicle maintenance costs really are, and, more important, why.

APPROACHES AND SCOPE

As shown below in this section, one of the primary characteristics of current maintenance cost estimates is their diversity. Seldom will two independent estimates agree closely. One reason for this is the variety of approaches that have been taken and the variation in scope of the different techniques.

The most obvious difference is between the top-down (macro) approach and the bottom-up (micro) approach. In the macro approach, illustrated by a 1971 TACOM study [27], the total cost of supporting the entire vehicle fleet (parts, labor, transportation, storage, and inventory control point support) is estimated from Army-level programming documents; this cost is then allocated among the various vehicle types composing the fleet. In the micro approach (used by all other sources we have seen), data on maintenance cost per mile or per year are collected on individual vehicles. These two approaches

produce widely varying estimates, with the macro results much higher, probably because of the inclusion of some costs that, for all practical purposes, are probably fixed (e.g. the cost of maintaining a depot system). In a similar fashion, all sources that use labor rates (cost per direct person-hour) use burdened rates, which include the costs of supervisory and administrative overhead, installation support, and nonproductive time; some of this overhead is probably fixed, at least for the moderate reductions in direct labor requirements that might be brought about by the introduction of diagnostic aid systems.

Another source of variation is the inclusion (or omission) of vehicle usage effects; these are most apparent when comparing test data (where vehicles are operated 20,000 miles in 6 months) with more typical field operation (6000 miles per year). Since some scheduled maintenance is prescribed on a time-or-miles (whichever comes first) basis, the cost of scheduled maintenance in field operation is spread over a smaller number of miles, thus driving up the maintenance cost per mile. Cost per mile figures must be used with care; besides the scheduled maintenance effect just discussed, vehicles tend to require more intensive maintenance as they accumulate mileage (and perhaps also as they merely age in years)--thus more maintenance would be required between 20,000 and 25,000 miles than between 5000 and 10,000 miles.*

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*Primarily as major assemblies (engines, transmissions) begin to be overhauled or replaced. AMSAA's useful life studies [9,17,18] attempt to determine the point at which total system cost per mile is at a minimum.

COMPARISON OF 1/4 TON TRUCK DATA

Table 18 summarizes the maintenance cost data available for the 1/4 ton truck, model M151A1. The "TACOM COMPTROLLER" data* represent the official position; all other sources shown in this table have been discussed in Sec. V and above in Sec. VI. Additional information is presented in Tables 19 and 20.

Immediately apparent is the wide variation in annual maintenance cost; part of this variation is of course due to mileage effects, but differences persist when the numbers are translated to a cost-per-mile basis. In a similar fashion, part of the cost difference is due to the different labor rates and parts costs** used, but the differences persist in the figures for maintenance person-hours per 1000 miles and in the constant-dollar costs (Table 21).

The largest variation is that between the results from the first three sources (which use a micro approach based on field or test data) and those from the last two sources (which use a macro approach based on the use of MACRIT labor requirments and allocation of total fleet parts costs). However, comparisons of 1/4 ton truck data may exaggerate the differences between the micro and macro approaches; the allocation methods used in Ref. 27 may overestimate the costs of simple vehicles like the 1/4 ton truck and underestimate those for complex vehicles like the tank.

*Provided by Harry Douglas of TACOM, 1976.

**Very little information is available on the variation in parts costs over time.

Table 18

SUMMARY OF MAINTENANCE COST DATA BY SOURCE--1/4 TON TRUCK (M151A1)

Data Source	Number of Vehicles	Annual Cost per Vehicle (Cost per mile)			Annual Mileage	Maintenance Person-Hours per 1000 Miles	Burdened Labor Rate	Maintenance Levels Included	Parts Cost Method	Year of Estimate[a]
		Total	Parts	Labor						
AMSAA (TAERS)	8345	$390 (6.5¢)	$204 (3.4¢)	$186 (3.1¢)	6000	5.1	$6.02	ORG DS GS	Individual parts	1975
MMC (SDC) (Worldwide)	1873	$875 (13.4¢)	$620 (9.5¢)	$255 (3.9¢)	6528	6.3	$6.20	ORG DS GS	Individual parts	1974
ARENBD (TEST)[b]	1	--	--	--	--	4.1	--	ORG DS (No GS actions required)	--	1969
STE/ICE Study	(c)	$2547 (63.7¢)	$1058[d] (26.4¢)	$1489 (37.2¢)	4000	50.5	$7.37	ORG DS GS	Allocated total	FY 1976
TACOM Comptroller (Worldwide)	(c)	$1467 (50.9¢)	$360 (12.5¢)	$1107 (38.4¢)	2880	50	$7.61	ORG DS GS	Based on "demand"	FY 1975

[a] Costing year (when known); otherwise year of documentation; costs adjusted to FY 1975 dollars are shown in Table 21, p. 91.

[b] No cost data in test report.

[c] Not applicable; labor costs based on MACRIT.

[d] These parts costs include depot parts and the costs of transportation, storage, and ICP support. STE/ICE costs adjusted to exclude these costs are shown in Table 21.

Table 19

BASIC INFORMATION--1/4 TON TRUCK DATA

Item	AMSAA (TAERS)	MMC (SDC)	ARENBD (TEST)	STE/ICE Study	TACOM Comptroller
Dates data gathered	1965-1969	2/72-1/74	7/68-1/69	--	--
Number of vehicles	8345 (Worldwide) 6615 (CONUS) 1054 (Europe) 676 (Pacific)	1873 (Worldwide) 812 (CONUS) 910 (Europe) 151 (Pacific)	1	--	--
Number of miles, in millions	84.2 (Worldwide) 66.1 (CONUS) 9.1 (Europe) 9.0 (Pacific)	16.0 (Worldwide) 4.6 (CONUS) 10.2 (Europe) 1.1 (Pacific)	20,077	--	--
Annual mileage per vehicle	6000	6528 (Worldwide) 4592 (CONUS) 7817 (Europe) 8623 (Pacific)	--	4000	2880

SOURCES: Refs. 3, 8-10, and personal communication from Harry Douglas of TACOM, 1976.

Additional information on the data collection is shown in Table 19, and includes breakouts by geographical area when applicable. Table 20 expands the total costs, the parts costs, and the labor costs. Even within a single data source (SDC) costs vary considerably; this may be due to geographical differences in vehicle use and maintenance, more accurate reporting from some areas, or different mixes of new and old vehicles. Table 21 attempts to reconcile some of the data discrepancies in four of the data sources. Mileage effects have again been accounted for by presenting all costs on a cost-per-mile basis. In addition, a standard labor rate has been assumed, and all costs have been adjusted to FY 1975 by assuming a parts cost inflation rate of 10 percent per year. This procedure tends to increase the total cost from AMSAA (TAERS) and MMC (SDC) worldwide, while lowering the total cost from the TACOM Comptroller.

Table 20

SUMMARY OF COSTS FOR THE 1/4 TON TRUCK

Item	AMSAA (TAERS)	MMC (SDC)	ARENBD (TEST)	STE/ICE Study	TACOM Comptroller
Parts Costs					
Parts cost per mile	3.4¢	9.5¢ (Worldwide) 6.3¢ (CONUS) 11.7¢ (Europe) 3.0¢ (Pacific)	(a)	26.4¢[b]	12.5¢
Annual parts cost (at annual mileage shown in Table 19)	$204	$620 (Worldwide) $289 (CONUS) $915 (Europe) $259 (Pacific)	(a)	$1058[b]	$360
Labor Costs					
Maintenance person-hours per 1000 miles	5.1	6.3 (Worldwide) 7.8 (CONUS) 5.6 (Europe) 5.5 (Pacific)	4.1	50.5	50[c]
Burdened labor rate[d]	$6.02	$6.20 (Worldwide) $5.80 (CONUS) $6.48 (Europe) $6.79 (Pacific)	--	$7.37	$7.61 (Worldwide)[c] $7.17 (CONUS) $7.83 (Europe) $8.17 (Pacific)
Labor cost per mile	3.1¢	3.9¢ (Worldwide) 4.5¢ (CONUS) 3.6¢ (Europe) 3.7¢ (Pacific)	--	37.2¢	38.4¢ (Worldwide)
Annual labor cost (at annual mileage shown in Table 19)	$186	$255 (Worldwide) $207 (CONUS) $281 (Europe) $319 (Pacific)	--	$1489	$1107
Total Costs					
Total cost per mile	6.5¢	13.4¢ (Worldwide) 10.8¢ (CONUS) 15.3¢ (Europe) 6.7¢ (Pacific)	--	63.7¢	50.9¢
Annual total cost (at annual mileage shown in Table 19)	$390	$875 (Worldwide) $496 (CONUS) $1196 (Europe) $578 (Pacific)	--	$2547	$1467

SOURCES: Refs. 3, 8-10, and personal communication from Harry Douglas of TACOM, 1976.

[a]Cannot be calculated because of missing stock numbers for some of the parts consumed.

[b]These parts costs include depot parts and the costs of transportation, storage, and ICP support. STE/ICE costs adjusted to exclude these costs are shown in Table 21.

[c]Estimated.

[d]Cost per person-hour of direct productive labor, including supervisory and administrative overhead and cost of plant maintenance and utilities.

Table 21

ANNUAL MAINTENANCE COSTS ADJUSTED TO
FY 1975 DOLLARS (M151A1)

(Cost per mile in parentheses)[a]

Data Source	Labor[b]	Parts[c]	Total
AMSAA (TAERS)	\$228 (3.8¢)	\$227 (3.8¢)	\$455 (7.6¢)
MMC (SDC) (Worldwide)	\$303 (4.6¢)	\$775 (11.9¢)	\$1078 (16.5¢)
STE/ICE Study	\$1489 (37.2¢)	\$1058 (26.4¢)[d]	\$2547 (63.7¢)
		\$545 (13.6¢)[e]	\$2034 (50.9¢)[e]
TACOM Comptroller	\$1072 (37.2¢)	\$360 (12.5¢)	\$1432 (49.7¢)

[a]Annual mileages are AMSAA (TAERS), 6000; MMC (SDC), 6528; STE/ICE Study, 4000; and TACOM Comptroller, 2880.

[b]Burdened labor rate = \$7.37.

[c]Assuming inflation of 10 percent per year from FY 1973 to FY 1975 and that AMSAA (TAERS) parts costs were in FY 1974 dollars, MMC (SDC) were in FY 1973 dollars, STE/ICE Study were in FY 1975 dollars, and TACOM Comptroller, FY 1975 dollars.

[d]These parts costs include some depot parts costs, and the costs of transportation, storage, and Inventory Control Point (ICP) support.

[e]Adjusted to exclude depot parts costs, transportation, storage and ICP support.

Thus, to some degree at least, the different costs have moved closer together. However, a rather large discrepancy still exists.

Which numbers are "correct?" A variety of opinions exist on both the quality of the data sources and the inclusion or exclusion of certain costs--considerable partisanship is evident, both among different Army agencies and among different offices within the same agency. Nevertheless, most people believe that 6 cents per mile should be closer to the truth than 60 cents per mile. This is a critical question when evaluating diagnostic equipment, since the equipment's economic justification depends on the amount of leverage it exerts on maintenance costs and on the magnitude of those maintenance costs before the diagnostic equipment is introduced.

The cost-benefit analysis procedure used in an RCA/TACOM study of the STE/ICE diagnostic aid system is summarized in Table 22, which is based on Ref. 3. Total vehicle maintenance cost was estimated, broken down into the elements that STE/ICE was assumed to affect, and the improvements (cost savings) resulting from STE/ICE introduction were calculated. As with any such analysis, if total costs are greatly reduced, or if a significant portion is fixed and therefore unaffected by diagnosis, the resultant cost savings will be reduced

Table 22

STE/ICE STUDY PROCEDURES

(1/4 ton truck, using diagnostic connector assembly)

- Total annual maintenance cost = \$2547 (parts = \$1058, labor = \$1489)
  - Labor = \$1489 (from MACRIT; 202.1 maintenance person-hours × \$7.37)
    - Organizational labor = \$537 (72.8 maintenance person-hours × \$7.37)
      - Unscheduled organizational labor = \$177 (0.33 of organizational labor)
        - Fault isolation labor = \$106 (0.60 of unscheduled organizational labor)
        - <u>STE/ICE saving in fault isolation labor = \$26</u>

          (0.243 of fault isolation labor = 0.30 applicability × 0.90 utilization × 0.90 improvement)
      - Scheduled organizational labor = \$359 (0.67 of organizational labor)
        - Test/inspect labor = \$36 (0.10 of scheduled organizational labor)
        - <u>STE/ICE saving in test/inspect labor = \$4</u>

          (0.108 of test/inspect labor = 0.15 applicability × 0.80 utilization × 0.90 improvement)
    - <u>Total annual STE/ICE saving in organizational labor = \$30</u>
  - Parts = \$1058 (from 1971 TACOM study)[a]
    - Unscheduled parts = \$952 (0.90 of total parts)
      - Faulty malfunction diagnosis parts = \$286 (0.30 of unscheduled parts)
      - <u>STE/ICE saving in faulty malfunction diagnosis parts = \$64</u>

        (0.224 of faulty malfunction diagnosis parts = 0.30 applicability × 0.90 utilization × 0.83 improvement)
    - <u>Total annual STE/ICE saving in parts = \$64</u>
- <u>Total annual STE/ICE savings = \$94 per vehicle per year</u>

[a]The TACOM study [27] estimates the total annual maintenance support costs for the entire vehicle fleet, subtracts labor costs, and allocates the residual to each vehicle type in proportion to its density and direct maintenance person-hour requirement (from MACRIT). Parts costs thus include the parts themselves, transportation, storage, and ICP support.

and the diagnostic aid system may no longer be economically justifiable.

As shown in Table 22, the evaluation procedure depends upon MACRIT input both for labor costs and to allocate fleet parts costs among vehicle types. At this point we should look more closely at the MACRIT process.

We mentioned earlier that the commodity commands (TACOM for land vehicles) are responsible for estimating the direct productive maintenance person-hours required per vehicle per year. Figure 7 shows TACOM's estimate for the 1/4 ton truck. Total time is 202.1 person-hours (assuming 4000 miles of operation per year),* broken out by maintenance level and Military Occupational Specialty. TRADOC then calculates authorized TO&E spaces by incorporating indirect productive time, nonproductive time, movement time, available time, and equipment density, as follows:

$$\text{number of spaces} = \text{equipment density} \times \frac{\text{direct productive maintenance person-hours} + \text{indirect productive maintenance person-hours}}{\text{available maintenance person-hours} - \text{nonproductive maintenance person-hours} - \text{movement time}}$$

In practice, indirect productive maintenance person-hours = 40 percent of direct, available = (12 hours/day) x (365 days/year) = 4380, nonproductive hours = 24 percent of available = .24 (4380) = 1051, and movement time = 830 (for a combat TO&E) [28], so the 35 1/4 ton trucks in a tank battalion will generate

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*At an assumed average speed of 20 miles per hour, this implies one direct productive maintenance person-hour per operating hour.

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MAINTENANCE MANHOUR REQUIREMENTS

DATE: [illegible] SEP 1975

TO: COMMANDING OFFICER
USAMC LOGISTICS DATA CENTER
LEXINGTON - BLUE GRASS ARMY DEPOT
LEXINGTON, KENTUCKY [illegible]

FROM: USATACOM
Warren, Michigan 48090

1. THE DIRECT ANNUAL MAN-HOUR DATA LISTED BELOW ARE SUBMITTED FOR [illegible]

2. END ITEM, SYSTEM OR ASSEMBLAGE

2a. FSN: 2320-763-1092

2b. NOMENCLATURE: TRUCK UTILITY 1/4 TON 4x4 W/E M151A1

2c. SB 700-20 LIN NO.: X60833

2d. TYPE CLASSIFIED: B 8285 71

3. COMPUTATION BASIS: 4000 MILES/YR ROUNDS ____ HOURS ____ TONS [ ] OTHER [illegible]

4. COMPUTATION DATA SOURCES

- [X] MAINTENANCE ENGINEERING ESTIMATES (includes contractor developed data)
- [ ] MAINTENANCE ENGINEERING ANALYSIS
- [X] SERVICE TESTS
- [ ] CONFIRMATORY TESTS
- [ ] SPECIAL OPERATIONAL DATA
- [X] THE ARMY MAINTENANCE MANAGEMENT SYSTEM (TAAMS) DATA

5. ANNUAL MANHOURS REQUIRED (BY MOS AND CATEGORY OF MAINTENANCE)

MOS CODE a	MOS TITLE b	OPERATOR/CREW c	ORG d	DS e	GS f	[illegible]		
								(%)
	CREW TIME	146.0						
63B	Wheel Vehicle Repairman		72.8	3.8	—0—		76.6	(38)
63G	Fuel & Elect. Sys. Repairman			15.7	0.8		16.5	(8)
63H	Engine & Powertrain Repairman			65.8	43.2		109.0	(54)
			72.8	85.3	44.0		202.1	
		%	36	42	22		100	

AMC FORM 1 MAY 72 1947-R

Fig. 7— TACOM input to MACRIT

$$(35)\ \frac{(202.1)(1.4)}{(4380 - 1051 - 830)} = 4.0 \text{ TO\&E maintenance spaces} .$$

A study of the MACRIT process [15] gives reasons to criticize many of these procedures. In particular, the commodity commands (especially TACOM) lack justification for their direct maintenance person-hour figures. In making these estimates, TACOM assumed that scheduled maintenance actions are as prescribed by the appropriate technical manuals, and that vehicle component life and use rates are such that every unscheduled maintenance action will be performed once every three years (12,000 miles at the assumed usage of 4000 miles per year for tactical vehicles) [27].* This probably overstates maintenance requirements, especially at general support level, where the 1/4 ton truck Maintenance Allocation Chart (MAC) shows only block repair, engine overhaul, transmission/transfer repair and overhaul, differential repair, and steering gear overhaul, although the MAC does not necessarily show all possible actions. According to the MACRIT study, both MACRIT factors and calculation procedures should be changed--"baseline" direct person-hour requirements should be estimated in a controlled environment, then adjusted to account for field and combat conditions.

This completes our discussion of currently available data and sources--many difficulties exist, and the data were not completely satisfactory for our purposes, although they did provide some useful

*A use rate of 1000 miles per year was assumed for combat vehicles.

benchmarks. Diagnostic aid systems usually affect the cost of maintenance performed on the various vehicle subsystems, but to obtain data by subsystem (e.g. from TAERS) would be a monumental data processing task.* Some recent work [35] has, however, made such estimates based on judgments by experienced maintenance personnel. A group of Army NCOs having an aggregate 200 years of vehicle maintenance experience was asked to estimate maintenance frequencies and parts and labor requirements for 1/4 ton trucks operated for 120 days (6000 miles) in a European wartime scenario. Estimates included extensive lists of person-hours and parts required at each maintenance level, broken down by vehicle component and type of action (repair, replace, service, etc.). These data were subsequently condensed to a more meaningful form and were presented in Sec. III.

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*Personal communication from Ray Bell of AMSAA, 1976.

VII. FINDINGS AND CONCLUSIONS

The impacts of diagnostic aid systems on maintenance costs depend on the level of maintenance costs in the absence of diagnosis, the magnitudes of the problems that increase maintenance costs to higher-than-necessary levels, and the effectiveness of the diagnostic aid systems in ameliorating these problems.

The problems that increase the frequency of maintenance (i.e., decrease vehicle reliability) are manufacturing faults, improper operation/neglect, and maintenance-induced faults; those that increase the cost of maintenance (i.e., decrease vehicle maintainability) are inefficient fault isolation, faulty malfunction diagnosis, late detection of faults, excessive rework, and low productivity.

Diagnostic aid systems perform one or more functions that act to reduce the magnitude of maintenance problems; these diagnostic functions are use monitoring, health monitoring, failure prediction, failing/failure detection, fault isolation, mechanic education, and repair verification.

Our study has taken an approach that can be applied to any diagnostic aid system, whereas other studies have been concerned with specific systems and considered only the fault isolation function.

The difference between maintenance costs in the absence of diagnosis and those with all maintenance problems eliminated is a measure of the potential maximum leverage for diagnostic aid systems. A vehicle that seldom needs repair and is easy and cheap to fix is

not a good candidate for the use of diagnostic aids. The methodology developed in this study was implemented in two models, the CSM and MADAM. If the necessary inputs can be obtained or estimated, these models can be used to identify the most important maintenance problems, examine the effects of changes in problem magnitudes and/or diagnostic effects, and estimate the potential savings achievable from deploying a particular diagnostic aid system.

The most serious limitation of this approach is a lack of good data in all areas--current maintenance costs, problem magnitudes, and diagnostic impacts. Some data do not exist at all; some that do exist are questionable, and discrepancies and inconsistencies occur among different data sources. Scheduled maintenance services and intervals are specified by Army manuals, but data suggest that some scheduled maintenance is not done. Other scheduled maintenance requirements are under revision and may be eliminated. Unscheduled maintenance data are available, but data from different sources are often inconsistent. Other data, such as vehicle use profiles, are nonexistent.

Since the early 1960s, the Army has employed several vehicle data collection schemes. TAERS, in use from 1962 until 1969, was not an effective data system although it was extremely extensive. Consequently, the mass of information contained within this data base is neither complete nor usable without a great deal of additional processing. SDC, instituted in 1972, is undoubtedly a better system, although the data obtained from it are also sometimes questionable.

In our opinion, intense SDC* plans are the best existing or attempted collection procedures. However, an intense SDC requires a long lead time for justification and implementation and can be very costly. TAERS data are too extensive in one sense, and not extensive enough in others, and SDC data may be too specific to be widely applicable unless the plan is carefully designed and controlled.

Another attempt by the Army to assure the collection and utilization of more complete data is the O&SCMIS (Operating and Support Cost Management Information System), outlined in Ref. 36. Three alternative collection procedures are examined: (1) current SDC, (2) intense SDC, and (3) a cost accounting system. For the present, on-going SDC plans will be used to provide the necessary data. In the future (tentatively by FY 1978), intense SDC plans will be implemented on selected equipment types, and an automated system to store, process, and disseminate O&S costs will be utilized. Additional equipment types (including combat vehicles) will be included as data become available.

The Army has made a number of proposals aimed at aiding in data management. One of these, the Vehicle Technical Management Information System (VETMIS), is being examined by the Tank-Automotive Commands [23]; a computerized data system, it will combine development testing, initial, and in-process production test data with existing field data. Another program is Logistics Support

*Intense (fully controlled) SDC differs from current SDC in that full-time trained personnel are responsible for recording and collecting the data. In Ref. 36 it is estimated that an intense SDC requires from six to ten times as many full-time people.

Analysis (LSA) [22]; LSA determines support requirements in terms of repair parts, skills, test equipment, and facilities, and examines the merits of replacement versus repair at each maintenance level. A third program is SAMS [37], intended to reduce, simplify, and standardize input forms, record documents, reporting requirements, and data flows throughout the Army. There is no doubt that the Army is aware of its data problems, but most past attempts to correct them have concentrated on data processing schemes. Good data processing is fine--if the data are of value.

Several recommendations have recently been made regarding the types of data that should be collected and the methods by which the collection should be accomplished. One study [16] emphasizes the importance of a vehicle use profile. However, no program of this type has been instituted. The MACRIT study [15] makes recommendations regarding a better method of calculating TO&E spaces, but this area is a sensitive one. Because of differing procurement philosophies, management goals, and operating procedures, commercial experience (from trucking, taxi, and car rental fleets, etc.) is not a good analog for Army experience.

In the Rand study of diagnostic aid systems, two data gathering efforts have been instituted which should provide useful information. The first is a questionnaire* encompassing all aspects of land vehicle maintenance, including the utility of diagnostic aid systems.

*To be completed by the MAIT (Maintenance Assistance and Instruction Teams) in various commands and locations.

The second effort involves the design and testing of a Vehicle Monitor System (VMS), a device to record vehicle use, operating conditions, and maintenance actions.

Data problems are not unique to the Army, but they are complicated by fragmentation of data sources and the organizational structure of Army units (a mix of several equipment types in each unit rather than units organized around a single equipment type). In our opinion, however, the Army should devote more effort to data requirements, collection techniques, and quality, rather than to processing existing data.* Although estimates of annual maintenance support expenditures for the entire fleet are available, no one knows with certainty what it costs (or should cost) to maintain the various types of Army land vehicles.

The current state of vehicle maintenance data is such that parametric approaches are necessary. Models like the CSM and MADAM, which parametrically analyze diagnostic impacts on maintenance costs, are useful tools for clarification of relevant issues. Although models using this approach cannot determine the exact savings possible through the implementation of a diagnostic aid system, they can indicate the type of system that would be the most effective.

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*One example of a step in the right direction is the identification of Essential Elements of Information (EEIs) in the SAMS General System Description.[37]

APPENDIX

MADAM OUTPUT (Base Case)

1/4 TON TRUCK (M151A1) -- BASE CASE

INPUT DATA

	FREQUENCY CURVE F(T)=1-EXP((-T**B)/A)		PERSON HOURS CURVE F(PH)=1-EXP(-PH/C)	PARTS COST CURVE F(PC)=1-EXP(-PC/E)
SUBSYSTEM	A	B	C	E
1	20.00	1.00	4.00	60.00
2	5.00	1.00	1.00	20.00
3	5.00	1.00	1.00	30.00
4	5.00	1.00	1.00	15.00
5	15.00	1.00	3.00	40.00
6	10.00	1.00	2.00	25.00

LABOR RATE IS $ 7.37 PER PERSON HOUR

PERSON HOURS PER CLOCK HOUR ARE 1.80

MILES OF OPERATION ARE 72.0 THOUSAND AT 6.0 THOUSAND PER YEAR

FACTORS INFLUENCING FREQUENCY

SUBSYSTEM	MFR FAULTS	IMP OP/NEGLECT	MIF(1000)	MIF(SEMI-ANNUAL)	MIF(ANNUAL)	MIF(USM)
1	.1000	.1500	.0	.0	.0	.0500
2	.1500	.0500	.0	.0	.0	.1000
3	.1500	.1000	.0	.0	.0	.1000
4	.1000	.1500	.0	.0	.0	.1000
5	.1000	.1500	.0	.0	.0	.1000
6	.1000	.1500	.0	.0	.0	.1000

DIAGNOSTIC IMPROVEMENTS

SUBSYSTEM	MFR FAULTS	IMP OP/NEGLECT	MIF(1000)	MIF(SEMI-ANNUAL)	MIF(ANNUAL)	MIF(USM)
1	.0	.0	.0	.0	.0	.0
2	.0	.0	.0	.0	.0	.0
3	.0	.0	.0	.0	.0	.0
4	.0	.0	.0	.0	.0	.0
5	.0	.0	.0	.0	.0	.0
6	.0	.0	.0	.0	.0	.0

MAINTENANCE INDUCED FAULTS(USM) ARE ALLOWED

FACTORS INFLUENCING PARTS COST AND LABOR

SUBSYSTEM	INEFF FAULT ISOL		FAULTY MAL DIAG		LATE DETECTION		EXCESS REWORK		LOW PROD	
	PARTS	LABOR	PARTS	LABOR	PARTS	LABOR	PARTS	LABOR	PARTS	LABOR
1	.0	.4000	.3000	.1000	.3000	.3000	.1000	.1000	.0	.1000
2	.0	.4000	.5000	.4000	.0100	.0100	.1000	.1000	.0	.1000
3	.0	.5000	.6000	.5000	.0100	.0100	.1000	.1000	.0	.1000
4	.0	.1000	.1500	.1000	.0100	.0100	.1000	.1000	.0	.1000
5	.0	.1500	.1000	.0500	.2000	.2000	.1000	.1000	.0	.1000
6	.0	.2000	.1000	.0500	.2000	.2000	.1000	.1000	.0	.1000

DIAGNOSTIC IMPROVEMENTS

SUBSYSTEM	INEFF FAULT ISOL		FAULTY MAL DIAG		LATE DETECTION		EXCESS REWORK		LOW PROD	
	PARTS	LABOR	PARTS	LABOR	PARTS	LABOR	PARTS	LABOR	PARTS	LABOR
1	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0
2	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0
3	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0
4	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0
5	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0
6	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0

SCHEDULED MAINTENANCE

EVERY 1.000 THOUSAND MILES:	
PERSON HOURS	2.00
PARTS COST($)	5.00
EVERY 3.000 THOUSAND MILES:	
PERSON HOURS	3.00
PARTS COST($)	15.00
EVERY 6.000 THOUSAND MILES:	
PERSON HOURS	4.00
PARTS COST($)	30.00

MAINTENANCE INDUCED FAULTS(SM) ARE NOT ALLOWED

UNSCHEDULED MAINTENANCE

SUBSYSTEM 1 ENGINE

MALFUNCTION	MILES(THOUSANDS)	PERSON HOURS	PARTS COST($)
1	15.300	13.06	136.05
2	29.835	13.06	136.05
3	44.370	13.06	136.05
4	58.905	13.06	136.05
5	THIS MALFUNCTION OCCURS AT 73.440 THOUSAND MILES		
		-------	-------
	TOTALS	52.26	$ 544.22
	LABOR COST (@ $ 7.37)	$ 385.13	

TOTAL COST FOR SUBSYSTEM 1 = $ 929.35

COST PER MILE FOR SUBSYSTEM 1 = 1.3 CENTS

UNSCHEDULED MAINTENANCE

SUBSYSTEM 2 FUEL

MALFUNCTION	MILES(THOUSANDS)	PERSON HOURS	PARTS COST($)
1	4.037	3.46	44.89
2	7.671	3.46	44.89
3	11.305	3.46	44.89
4	14.939	3.46	44.89
5	18.572	3.46	44.89
6	22.206	3.46	44.89
7	25.840	3.46	44.89
8	29.474	3.46	44.89
9	33.107	3.46	44.89
10	36.741	3.46	44.89
11	40.375	3.46	44.89
12	44.009	3.46	44.89
13	47.642	3.46	44.89
14	51.276	3.46	44.89
15	54.910	3.46	44.89
16	58.544	3.46	44.89
17	62.177	3.46	44.89
18	65.811	3.46	44.89
19	69.445	3.46	44.89
20	THIS MALFUNCTION OCCURS AT 73.079 THOUSAND MILES		
		-------	-------
	TOTALS	65.82	$ 852.97
	LABOR COST (@ $ 7.37)	$ 485.06	

TOTAL COST FOR SUBSYSTEM 2 = $1338.04

COST PER MILE FOR SUBSYSTEM 2 = 1.9 CENTS

UNSCHEDULED MAINTENANCE

SUBSYSTEM 3 ELECTRICAL

MALFUNCTION	MILES(THOUSANDS)	PERSON HOURS	PARTS COST($)
1	3.825	4.99	84.18
2	7.267	4.99	84.18
3	10.710	4.99	84.18
4	14.152	4.99	84.18
5	17.595	4.99	84.18
6	21.037	4.99	84.18
7	24.480	4.99	84.18
8	27.922	4.99	84.18
9	31.365	4.99	84.18
10	34.807	4.99	84.18
11	38.250	4.99	84.18
12	41.692	4.99	84.18
13	45.135	4.99	84.18
14	48.577	4.99	84.18
15	52.020	4.99	84.18
16	55.462	4.99	84.18
17	58.905	4.99	84.18
18	62.347	4.99	84.18
19	65.790	4.99	84.18
20	69.232	4.99	84.18
21	THIS MALFUNCTION OCCURS AT 72.675 THOUSAND MILES		
		-------	-------
	TOTALS	99.76	$1683.50
	LABOR COST (@ $ 7.37)	$ 735.25	

TOTAL COST FOR SUBSYSTEM 3 = $2418.75

COST PER MILE FOR SUBSYSTEM 3 = 3.4 CENTS

UNSCHEDULED MAINTENANCE

SUBSYSTEM 4 COOLING

MALFUNCTION	MILES(THOUSANDS)	PERSON HOURS	PARTS COST($)
1	3.825	1.54	19.81
2	7.267	1.54	19.81
3	10.710	1.54	19.81
4	14.152	1.54	19.81
5	17.595	1.54	19.81
6	21.037	1.54	19.81
7	24.480	1.54	19.81
8	27.922	1.54	19.81
9	31.365	1.54	19.81
10	34.807	1.54	19.81
11	38.250	1.54	19.81
12	41.692	1.54	19.81
13	45.135	1.54	19.81
14	48.577	1.54	19.81
15	52.020	1.54	19.81
16	55.462	1.54	19.81
17	58.905	1.54	19.81
18	62.347	1.54	19.81
19	65.790	1.54	19.81
20	69.232	1.54	19.81
21	THIS MALFUNCTION OCCURS AT 72.675 THOUSAND MILES		
		-------	-------
	TOTALS	30.79	$ 396.12
	LABOR COST (a $ 7.37)	$ 226.93	

TOTAL COST FOR SUBSYSTEM 4 = $ 623.05

COST PER MILE FOR SUBSYSTEM 4 = 0.9 CENTS

UNSCHEDULED MAINTENANCE

SUBSYSTEM 5 TRANSMISSION/DRIVE TRAIN

MALFUNCTION	MILES(THOUSANDS)	PERSON HOURS	PARTS COST($)
1	11.475	5.73	61.73
2	21.802	5.73	61.73
3	32.130	5.73	61.73
4	42.457	5.73	61.73
5	52.785	5.73	61.73
6	63.112	5.73	61.73
7	THIS MALFUNCTION OCCURS AT 73.440 THOUSAND MILES		
		-------	-------
	TOTALS	34.40	$ 370.37
	LABOR COST (@ $ 7.37)	$ 253.53	

TOTAL COST FOR SUBSYSTEM 5 = $ 623.90

COST PER MILE FOR SUBSYSTEM 5 = 0.9 CENTS

UNSCHEDULED MAINTENANCE

SUBSYSTEM 6 BRAKES/SUSPENSION

MALFUNCTION	MILES(THOUSANDS)	PERSON HOURS	PARTS COST($)
1	7.650	4.06	38.58
2	14.535	4.06	38.58
3	21.420	4.06	38.58
4	28.305	4.06	38.58
5	35.190	4.06	38.58
6	42.075	4.06	38.58
7	48.960	4.06	38.58
8	55.845	4.06	38.58
9	62.730	4.06	38.58
10	69.615	4.06	38.58
11	THIS MALFUNCTION OCCURS AT 76.500 THOUSAND MILES		
		-------	-------
	TOTALS	40.61	$ 385.80
	LABOR COST (@ $ 7.37)	$ 299.30	

TOTAL COST FOR SUBSYSTEM 6 = $ 685.10

COST PER MILE FOR SUBSYSTEM 6 = 1.0 CENTS

ORDERED MAINTENANCE ACTIONS

UNSCHEDULED MAINTENANCE

ACTION	MILES(1000)	SUBSYSTEM	MALFUNCTION	PERSON HOURS		LABOR $		PARTS $		TOTAL $	
				THIS	CUM	THIS	CUM	THIS	CUM	THIS	CUM
1	3.825	3	1	4.99	4.99	36.76	36.76	84.18	84.18	120.94	120.94
2	3.825	4	1	1.54	6.53	11.35	48.11	19.81	103.98	31.15	152.09
3	4.037	2	1	3.46	9.99	25.53	73.64	44.89	148.87	70.42	222.51
4	7.267	3	2	4.99	14.98	36.76	110.40	84.18	233.05	120.94	343.45
5	7.267	4	2	1.54	16.52	11.35	121.75	19.81	252.86	31.15	374.60
6	7.650	6	1	4.06	20.58	29.93	151.68	38.58	291.44	68.51	443.11
7	7.671	2	2	3.46	24.04	25.53	177.21	44.89	336.33	70.42	513.54
8	10.710	3	3	4.99	29.03	36.76	213.97	84.18	420.50	120.94	634.47
9	10.710	4	3	1.54	30.57	11.35	225.32	19.81	440.31	31.15	665.63
10	11.305	2	3	3.46	34.04	25.53	250.85	44.89	485.20	70.42	736.05
11	11.475	5	1	5.73	39.77	42.25	293.10	61.73	546.93	103.98	840.03
12	14.152	3	4	4.99	44.76	36.76	329.86	84.18	631.11	120.94	960.97
13	14.152	4	4	1.54	46.30	11.35	341.21	19.81	650.91	31.15	992.12
14	14.535	6	2	4.06	50.36	29.93	371.14	38.58	689.49	68.51	1060.63
15	14.939	2	4	3.46	53.82	25.53	396.67	44.89	734.39	70.42	1131.05
16	15.300	1	1	13.06	66.89	96.28	492.95	136.05	870.44	232.34	1363.39
17	17.595	3	5	4.99	71.87	36.76	529.72	84.18	954.61	120.94	1484.33
18	17.595	4	5	1.54	73.41	11.35	541.06	19.81	974.42	31.15	1515.48
19	18.572	2	5	3.46	76.88	25.53	566.59	44.89	1019.31	70.42	1585.90
20	21.037	3	6	4.99	81.87	36.76	603.35	84.18	1103.49	120.94	1706.84
21	21.037	4	6	1.54	83.41	11.35	614.70	19.81	1123.29	31.15	1737.99
22	21.420	6	3	4.06	87.47	29.93	644.63	38.58	1161.87	68.51	1806.50
23	21.802	5	2	5.73	93.20	42.25	686.88	61.73	1223.60	103.98	1910.49
24	22.206	2	6	3.46	96.66	25.53	712.41	44.89	1268.50	70.42	1980.91
25	24.480	3	7	4.99	101.65	36.76	749.18	84.18	1352.67	120.94	2101.85
26	24.480	4	7	1.54	103.19	11.35	760.52	19.81	1372.48	31.15	2133.00
27	25.840	2	7	3.46	106.66	25.53	786.05	44.89	1417.37	70.42	2203.42
28	27.922	3	8	4.99	111.64	36.76	822.82	84.18	1501.54	120.94	2324.36
29	27.922	4	8	1.54	113.18	11.35	834.16	19.81	1521.35	31.15	2355.51
30	28.305	6	4	4.06	117.24	29.93	864.09	38.58	1559.93	68.51	2424.02
31	29.474	2	8	3.46	120.71	25.53	889.62	44.89	1604.82	70.42	2494.45
32	29.835	1	2	13.06	133.77	96.28	985.90	136.05	1740.88	232.34	2726.78
33	31.365	3	9	4.99	138.76	36.76	1022.67	84.18	1825.05	120.94	2847.72
34	31.365	4	9	1.54	140.30	11.35	1034.01	19.81	1844.86	31.15	2878.87
35	32.130	5	3	5.73	146.03	42.25	1076.27	61.73	1906.59	103.98	2982.86
36	33.107	2	9	3.46	149.50	25.53	1101.80	44.89	1951.48	70.42	3053.28
37	34.807	3	10	4.99	154.49	36.76	1138.56	84.18	2035.66	120.94	3174.22
38	34.807	4	10	1.54	156.03	11.35	1149.91	19.81	2055.46	31.15	3205.37
39	35.190	6	5	4.06	160.09	29.93	1179.84	38.58	2094.04	68.51	3273.88
40	36.741	2	10	3.46	163.55	25.53	1205.37	44.89	2138.93	70.42	3344.30
41	38.250	3	11	4.99	168.54	36.76	1242.13	84.18	2223.11	120.94	3465.24
42	38.250	4	11	1.54	170.08	11.35	1253.48	19.81	2242.92	31.15	3496.39
43	40.375	2	11	3.46	173.54	25.53	1279.01	44.89	2287.81	70.42	3566.81
44	41.692	3	12	4.99	178.53	36.76	1315.77	84.18	2371.98	120.94	3687.75
45	41.692	4	12	1.54	180.07	11.35	1327.11	19.81	2391.79	31.15	3718.90
46	42.075	6	6	4.06	184.13	29.93	1357.04	38.58	2430.37	68.51	3787.41
47	42.457	5	4	5.73	189.86	42.25	1399.30	61.73	2492.10	103.98	3891.40
48	44.009	2	12	3.46	193.33	25.53	1424.83	44.89	2536.99	70.42	3961.82
49	44.370	1	3	13.06	206.39	96.28	1521.11	136.05	2673.05	232.34	4194.16
50	45.135	3	13	4.99	211.38	36.76	1557.87	84.18	2757.22	120.94	4315.09
51	45.135	4	13	1.54	212.92	11.35	1569.22	19.81	2777.03	31.15	4346.25
52	47.642	2	13	3.46	216.38	25.53	1594.75	44.89	2821.92	70.42	4416.67

53	48.577	3	14	4.99	221.37	36.76	1631.51	84.18	2906.09	120.94	4537.61
54	48.577	4	14	1.54	222.91	11.35	1642.86	19.81	2925.90	31.15	4568.76
55	48.960	6	7	4.06	226.97	29.93	1672.79	38.58	2964.48	68.51	4637.27
56	51.276	2	14	3.46	230.44	25.53	1698.32	44.89	3009.37	70.42	4707.69
57	52.020	3	15	4.99	235.42	36.76	1735.08	84.18	3093.55	120.94	4828.63
58	52.020	4	15	1.54	236.96	11.35	1746.43	19.81	3113.35	31.15	4859.78
59	52.785	5	5	5.73	242.70	42.25	1788.68	61.73	3175.08	103.98	4963.76
60	54.910	2	15	3.46	246.16	25.53	1814.21	44.89	3219.98	70.42	5034.19
61	55.462	3	16	4.99	251.15	36.76	1850.97	84.18	3304.15	120.94	5155.13
62	55.462	4	16	1.54	252.69	11.35	1862.32	19.81	3323.96	31.15	5186.28
63	55.845	6	8	4.06	256.75	29.93	1892.25	38.58	3362.54	68.51	5254.79
64	58.544	2	16	3.46	260.21	25.53	1917.78	44.89	3407.43	70.42	5325.21
65	58.905	3	17	4.99	265.20	36.76	1954.54	84.18	3491.60	120.94	5446.14
66	58.905	4	17	1.54	266.74	11.35	1965.89	19.81	3511.41	31.15	5477.30
67	58.905	1	4	13.06	279.81	96.28	2062.17	136.05	3647.46	232.34	5709.63
68	62.177	2	17	3.46	283.27	25.53	2087.70	44.89	3692.36	70.42	5780.05
69	62.347	3	18	4.99	288.26	36.76	2124.46	84.18	3776.53	120.94	5900.99
70	62.347	4	18	1.54	289.80	11.35	2135.81	19.81	3796.34	31.15	5932.14
71	62.730	6	9	4.06	293.86	29.93	2165.74	38.58	3834.92	68.51	6000.66
72	63.112	5	6	5.73	299.59	42.25	2207.99	61.73	3896.65	103.98	6104.64
73	65.790	3	19	4.99	304.58	36.76	2244.75	84.18	3980.82	120.94	6225.57
74	65.790	4	19	1.54	306.12	11.35	2256.10	19.81	4000.63	31.15	6256.73
75	65.811	2	18	3.46	309.58	25.53	2281.63	44.89	4045.52	70.42	6327.15
76	69.232	3	20	4.99	314.57	36.76	2318.39	84.18	4129.70	120.94	6448.08
77	69.232	4	20	1.54	316.11	11.35	2329.74	19.81	4149.50	31.15	6479.23
78	69.445	2	19	3.46	319.57	25.53	2355.27	44.89	4194.39	70.42	6549.65
79	69.615	6	10	4.06	323.64	29.93	2385.20	38.58	4232.97	68.51	6618.16

ANNUAL UNSCHEDULED MAINTENANCE COST = $ 551.51

UM COST PER MILE = 9.2 CENTS

MEAN MILES BETWEEN UMA = 911.

MEAN PERSON HOURS PER UMA = 4.1

MEAN PARTS COST PER UMA = $ 53.58

MAINTENANCE RATIO(UM) = 0.090
(MAINTENANCE PERSON HOURS/OPERATING HOUR)

IMPLICIT AVAILABILITY(UM) = 0.952

SCHEDULED MAINTENANCE

MILES(1000)	# OF INDEPENDENT OCCURRENCES	PERSON HOURS		LABOR $		PARTS $		TOTAL $	
		THIS	CUM	THIS	CUM	THIS	CUM	THIS	CUM
1.000	48	96.00	96.00	707.52	707.52	240.00	240.00	947.52	947.52
3.000	12	36.00	132.00	265.32	972.84	180.00	420.00	445.32	1392.84
6.000	12	48.00	180.00	353.76	1326.60	360.00	780.00	713.76	2106.60

ANNUAL SCHEDULED MAINTENANCE COST = $ 175.55

SM COST PER MILE = 2.9 CENTS

MEAN MILES BETWEEN SMA = 1000.

MEAN PERSON HOURS PER SMA = 2.5

MEAN PARTS COST PER SMA = $ 10.83

MAINTENANCE RATIO(SM) = 0.050
(MAINTENANCE PERSON HOURS/OPERATING HOUR)

ALL MAINTENANCE

LABOR COST ($)	PARTS COST ($)	TOTAL COST ($)
3711.79	5012.97	8724.76

ANNUAL TOTAL COST = $ 727.06

TOTAL COST PER MILE = 12.1 CENTS

MEAN MILES BETWEEN ALL MAINTENANCE ACTIONS = 477.

MEAN PERSON HOURS PER MAINTENANCE ACTION = 3.3

MEAN PARTS COST PER MAINTENANCE ACTION = $ 33.20

MAINTENANCE RATIO(ALL MAINTENANCE) = 0.140
(MAINTENANCE PERSON HOURS/OPERATING HOUR)

IMPLICIT AVAILABILITY(ALL MAINTENANCE) = 0.928

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